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CHEMICAL COMPOSITION AS A CRITERION IN IDENTIFYING METAMORPHOSED SEDIMENTS[1]

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I

In 1909 the writer contributed to this *Journal*[2] an article under the title given above. In the present pages it is his desire to correct some apparent misunderstandings of the import of the data there presented and to offer some additional data since obtained.

The idea that chemical composition may in some cases furnish a clue to the origin of a metamorphic rock is nothing new. It was formulated in general terms by Rosenbusch and has been given recognition by Grubenmann, Van Hise, Adams, and others.

The postulate is a very simple one, namely: that certain well-known and characteristic changes in chemical composition produced in the processes of rock weathering and assortment may be recognizable even when the resulting product has been dynamically metamorphosed.

The writer in his previous article attempted to test with some care the value of each of the chemical criteria which earlier writers had suggested, and the method adopted was the comparison of

[1] Published with the permission of the Director of the U.S. Geological Survey.

[2] *Jour. Geol.*, XVII (1909), 445–72.

analyses of a large number of sedimentary slates and schists with a much larger number of analyses of igneous rocks. Such a statistical study, the assembling of analyses which were selected judiciously but impartially, offered, he believed, a viewpoint from which the *rule* could be perceived in the midst of the numerous *exceptions* which special conditions introduce. The result of this study was to confirm in general the beliefs of the geologists who had earlier considered this problem. In addition conclusions were reached as to the relative critical value of various chemical relationships.

J. D. Trueman in a recent number of this *Journal*[1] summarized in a very useful manner the various criteria that had been applied for determining the origin of schists. In the section devoted to chemical criteria he recognized that these may be of service in some instances, but he seemed in general inclined to attribute small importance to them.

As Mr. Trueman was good enough to refer to my article on this subject, I wish here to consider some of the objections which he raised and to elucidate further certain of the arguments that were brought forward in the original paper. Mr. Trueman's untimely death last summer while engaged in geologic field work must be a source of deep regret to those who are familiar with his work and I take this opportunity to express my appreciation of the high value of the contribution he has made to the literature on metamorphism. Agreeing with most of his conclusions, if I take exception to a few of them it is in the belief that no true scientist regards his results as final but is eminently satisfied if his work stimulates others and contributes somewhat to the progress toward a more complete knowledge of Nature's laws.

The principal criteria which have been appealed to in support of sedimentary origin of a fresh crystalline schist are: (1) dominance of magnesia over lime, (2) dominance of potash over soda, (3) the presence of alumina in large excess over the 1:1 ratio necessary to satisfy the alkalies present. It should be particularly emphasized that the *amount of the excess* of potash, magnesia, or alumina is of great importance, a magnesia-lime ratio of 4:1 being immensely

[1] *Jour. Geol.*, XX, No. 4, pp. 300–311.

more significant than a $1\frac{1}{2}:1$ ratio, and 10 per cent excess alumina having several times the diagnostic value of a 5 per cent excess.

In attempting to compare in a general way the *relative* merits of various chemical criteria, the writer possibly conveyed a stronger impression of their individual worth and potency than he would at present desire to do. Few reputable physicians are content to diagnose a disease from a single symptom, but when several symptoms all point to a common cause a diagnosis may be made with security. To follow the parallel, the chemical relationships used as criteria are symptoms which considered singly might result from several causes, but taken collectively are known to result from only one[1] cause, rock weathering and assortment. In actual practice the geologist is seldom required to depend entirely upon chemical criteria but is aided in his diagnosis by structural and textural features as well.

The principal results of the writer's comparisons of analyses of meta-sedimentary with igneous rocks may be summed up in the following table in which the figures in parentheses show the number of analyses of each class of rocks entering into the comparison.

TABLE I

	Percentage Weight of MgO>CaO	Percentage Weight of $K_2O>Na_2O$	Percentage Weights of Both MgO>CaO and $K_2O>Na_2O$	Over 5 Per Cent Excess* Al_2O_3	Over 10 Per Cent Excess* Al_2O_3
Sedimentary slates	(79) 84 per cent	(74) 92 per cent	(74) 78 per cent	.....	.....
Pelite schists and gneisses	(30) 77 per cent	(30) 83 per cent	(30) 74 per cent	(30) 63 per cent	(30) 30 per cent
Igneous rocks of Washington's *Tables of Analyses*: Classes I and II	(1481) 8 per cent	(1481) $36\frac{1}{2}$ per cent	(1481) $4\frac{1}{2}$ per cent	(1892) Less than 3 per cent	(1892) About 0.6 per cent
Igneous rocks of Washington's *Tables of Analyses*: All other classes	(411) 35 per cent	(401) 14 per cent	(401) 7 per cent		

*By "Excess Al_2O_3" is meant the alumina in excess over the 1:1 ratio in which it is combined with lime and the alkalies in the aluminous silicates. If the "norm" is calculated according to the method of the *Quantitative Classification of Igneous Rocks*, this excess appears as corundum.

The meaning of the table may be made clearer by interpreting its third column. This column shows that of 74 analyses of sedi-

[1] A partial exception in hydrothermal metamorphism will be referred to later.

mentary slates 78 per cent showed a dominance both of magnesia over lime and of potash over soda. In 70 analyses of pelitic schists and gneisses this relationship is almost equally characteristic, holding in 74 per cent of the analyses. In the more siliceous igneous rocks (Classes I and II), on the other hand, dominance of magnesia over lime and of potash over soda occurs in only $4\frac{1}{2}$ per cent of the 1,481 analyses considered, and in the case of all the other igneous rocks (Classes III, IV, and V) in only 7 per cent of the 401 analyses considered. The contrast between igneous rocks and sediments shown in the other columns is also striking. Such wide differences as are here exhibited can hardly be fortuitous, and the nature of data upon which they are based would seem to recommend them to the serious consideration of geologists.

In criticism of the value of the potash-soda and magnesia-lime ratios as criteria of genesis, Mr. Trueman[1] states that "in the case of many, possibly in the majority of, igneous rocks *either* the MgO is in excess over the CaO or the K_2O over the Na_2O . . . ." and points out with perfect correctness that "the tables of Washington show that in the majority of igneous rocks *containing over 70 per cent of silica* the K_2O is in excess over Na_2O. . . . . Accordingly while the double relationship is apparently significant, the single ratios have but little value."

To the present writer there would seem to be no valid reason for restricting the comparison to those igneous rocks which show more than 70 per cent of silica, especially as these include nearly all of the greatest group of potash-rich rocks, the granites and rhyolites, and also as the average percentage of silica in the metasedimentary rocks with which they are compared is only 60 to 65 per cent. While the double relationship $\left\{\begin{matrix} K_2O > Na_2O \\ \text{and} \\ MgO > CaO \end{matrix}\right\}$ is the most significant and the single relationship of $K_2O > Na_2O$ or $MgO > CaO$ is of little or no critical importance when standing alone, the writer believes that either of these relations, if supported by notable excess of alumina, has very considerable critical value.

Each of the criteria suggested has its "limit of error" which

[1] *Op. cit.*, p. 301.

with the data at present available cannot be determined. For this reason the criteria cannot be applied automatically without the exercise of judgment and discretion on the part of the investigator. It should be especially remembered that if the rocks under investigation have been subjected, either before or after the development of their foliated structure, to severe igneous or hydrothermal

TABLE II

	I	II	III
SiO_2	57.35	49.59	61.62
Al_2O_3	16.29	14.91	19.98
Fe_2O_3	3.15	.52	3.46
FeO	4.36	10.46	2.57
MgO	2.41	2.02	1.24
CaO	5.66	1.96	.62
Na_2O	4.50	1.33	1.78
K_2O	3.39	3.51	5.35
H_2O-	.15	.16	.21 }
H_2O+	.70	3.17	2.23 }
TiO_2	1.07	1.03	.56
ZrO_2	tr.	none	
CO_2	.46	9.40	
P_2O_5	.70	.47	
MnO	.12	1.10	
Others	.24	.43	
Total	100.55	100.06	99.62

I. Fresh diorite porphyry 25 feet from vein, Wellington mine, Breckenridge, Colo. W. T. Schaller, analyst.

II. Altered diorite porphyry 10 feet from vein, Wellington mine, Breckenridge, Colo. W. T. Schaller, analyst.

III. Pinal schist, Ray district, Arizona. Analysis made for Dr. F. L. Ransome by R. C. Wells.

metamorphism, the criteria are not applicable, for such metamorphism involves important additions and losses of material. For example, analyses I and II of Table II taken from Dr. Ransome's report on the Breckenridge district, Colorado,[1] show that in the hydrothermal metamorphism of a diorite porphyry there has been a much greater depletion in lime than in magnesia and that there has been an accession of potash and loss of soda, yielding a rock in which the double relationship $\left\{\begin{matrix} K_2O > Na_2O \\ \text{and} \\ MgO > CaO \end{matrix}\right\}$ is present.

[1] F. L. Ransome, "Geology and Ore Deposits of the Breckenridge District, Colorado," *Prof. Paper U.S. Geol. Surv. No. 75* (1911), p. 96.

The same result is brought about by the hydrothermal alteration of monzonite porphyry in the Clifton-Morenci district as described by Lindgren,[1] and Dr. A. C. Spencer has shown the writer unpublished analyses exhibiting similar changes as a result of hydrothermal metamorphism of porphyry in the Ely district, Nevada. It is evident therefore that the chemical criteria must be applied only to those foliated rocks which the microscope shows have *not* been subsequently subjected to weathering or to igneous or hydrothermal metamorphism, in other words, to *fresh* foliated rocks. In those rare instances where igneous or hydrothermal metamorphism has affected the rocks previous to the development of foliation there should usually be some evidence of it in the presence of mineralization in associated schists.

An instance of the successful application of chemical criteria as an aid to determining the origin of a schist in a mining district is afforded by analysis III of Table II, hitherto unpublished, which I have been permitted to use through the courtesy of Dr. F. L. Ransome. This schist consists predominantly of quartz and sericite with subordinate chlorite, biotite, andalusite, magnetite, and zircon. It forms part of the Pinal schist of the Ray district, Arizona, which is shown by bands of pebbles, arkosic and quartzitic phases to be for the most part of sedimentary origin. This schist is older than the mineralization, and microscopic study indicates that the specimen analyzed has suffered no important mineral changes since the development of the foliation. It will be noted that there is about twice as much magnesia as lime in this rock and about three times as much potash as soda. Alumina is present to the extent of 10.30 per cent above that necessary to satisfy the lime and alkalies present. The strong development in this rock of these three chemical characteristics points to its having been subjected to the processes of weathering and assortment previous to metamorphism, in other words, indicates a sedimentary origin, and affords, the writer believes, a valuable *adjunct* to textural and structural evidences in interpreting the origin of the rock.

[1] W. Lindgren, "The Copper Deposits of the Clifton-Morenci District, Arizona," *Prof. Paper U.S. Geol. Surv., No. 43* (1905), p. 168.

II

The question of the value of chemical criteria is part of the much broader question of the extent to which transfer of material goes on in rocks during purely dynamic metamorphism. This is a problem of importance to geologists and one which has received little attention. The data at present available are of somewhat conflicting character. Certainly many who have worked in regions of metamorphic schists must have been impressed by the extent to which portions of the metamorphic series, originally different, have preserved their individuality. Dikes, though rendered schistose and perhaps pinched out in places, still show sharp borders giving no evidence of extensive interchange of material with the bordering rock; limestone beds in the series still show sharp borders after metamorphism, and original sedimentary beds may still be recognized as such by the development of *knoten* or of particular minerals in some of them and not in others. In rarer cases ore deposits have been deformed in dynamic metamorphism without destroying the integrity of the ore bodies or causing any migration of the ores into the wall rocks as in the case of the Milan, N.H., deposit described by Emmons.[1]

As the writer pointed out in his earlier paper,[2] many of the granite-gneisses of Georgia described by Dr. Watson are still normal granites in composition although showing marked evidence of dynamo-metamorphism. To quote Dr. Watson:[3] ". . . . the granite-gneisses differ from the more massive rock phases [granite] simply in the marked banded or foliated structure. These are secondary structures induced by profound and long-continued dynamo-metamorphism, acting on an originally massive rock, similar, in mineralogical and chemical compositions, to the existing massive granite areas studied."

If it can be shown that important transfers of material may take place during dynamo-metamorphism, it still remains to be determined whether such processes are common or exceptional in the

[1] W. H. Emmons, "Some Ore Deposits in Maine and New Hampshire," *Bull. U.S. Geol. Surv., No. 432* (1910), pp. 50–60.

[2] *Jour. Geol.*, XVII (1909), 450–51.

[3] *Bull. 9-a, Geol. Surv. of Georgia*, p. 263.

metamorphic rocks now exposed at the earth's surface. It is commonly supposed that under conditions of dynamo-metamorphism rocks are relatively dry and pore-space is reduced to a minimum and such conditions would appear to be particularly unfavorable for the transportation of material through long distances in solution. Certainly the writer has seen little in his personal experience with the crystalline schists of New England and the Rocky Mountains to suggest migration of material under such conditions through more than very small distances. A number of years ago the writer, by averaging a very large number of analyses of clays, shales, slates, and pelite schists, attempted to prepare a series of curves to illustrate the chemical changes during the metamorphism of a clay into a pelite schist. The data used were not regarded as sufficiently complete in all particulars to justify publishing the curves. They showed marked loss of water and carbon dioxide but were suggestive of considerable stability in most of the other constituents, with the possible exception of silica.

It is well known that the development of platy minerals is a characteristic feature in dynamo-metamorphism. From the department of geology of the University of Wisconsin has come the suggestion that this process may exert a controlling influence upon the composition of the rock, constituents unnecessary for the formation of the platy minerals being removed during the progress of the dynamo-metamorphism. While suggested as a general law, the actual evidence thus far offered in support of this hypothesis has involved only the expulsion of silica from highly siliceous rocks. The data offered by Mr. Trueman[1] in evidence of such transportation of silica in the Waterloo quartzite of Wisconsin are suggestive and all similar data should become a matter of record. It is shown that while some bands of sericite schist parallel the bedding planes of the quartzite, others transgress them, and it is argued that the sericite schist of these transgressing shear zones has been produced directly from the impure quartzite by the expulsion of silica during the shearing process. Other hypotheses are, however, worthy of consideration. The zones of sericite schist which transgress the bedding planes may represent

[1] *Op. cit.*, pp. 302–6.

fracture zones which later became the locus of shearing movements. All that is required to produce the chemical changes observed is the removal of silica by waters circulating along such fractures. It is also impossible in this region to eliminate the possible effect of igneous rocks as a source of energy which might result in such changes. The Waterloo quartzite outcrops only in small ledges separated by large areas covered by glacial drift. Pegmatites which appear to be earlier than the shearing of the quartzite cut this rock in certain of the ledges. Although no pegmatite outcrops at the locality where the samples analyzed were taken, it is impossible to say that it does not occur close by beneath the drift cover.

Whatever may be the facts in regard to the mobility of silica under certain conditions, it is beyond question that in the metamorphism of many sedimentary series the quartzite members preserve their integrity even when the associated argillaceous beds are rendered highly schistose, nor do the latter show any marked accession of silica. It has been suggested that a talc schist is the characteristic metamorphic equivalent of limestone as a sericite schist is of quartzite, but here again we are confronted with numerous field observations showing abrupt passages from crystalline limestones to argillaceous schists and to quartzites, even in severely metamorphosed series. Furthermore, with the possible exception of the expulsion of silica, the development of platy minerals during dynamo-metamorphism would seem to be a process ill suited to the accomplishment of any considerable changes in chemical composition, for the platy minerals that are characteristically developed in schists during dynamo-metamorphism are minerals of extremely variable composition, and the same elements enter into the makeup of a number of them. For this reason they are especially adapted to *accommodate* original differences in composition both through variation in the relative proportions of the different platy minerals developed and through variations in composition of each of these minerals.

WASHINGTON, D.C.
December, 1912

OBSERVATIONS ON THE FELDSPARS

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Leland Stanford Junior University

A PECULIAR PERTHITE FROM PORT HENRY, N.Y.[1]

An interesting variation of the albite-microcline intergrowth known as perthite was noticed among some specimens obtained from a mineral dealer. The body of the specimen is pale flesh-red microcline. On the basal pinacoidal {010} cleavage there are two intersecting sets of narrow, colorless albite strips, which are plates inserted parallel to the unit prism {110} (Fig. 1). The peculiarity is that the two sets of albite plates are twinned with respect to each other on the albite law. This can be demonstrated by holding

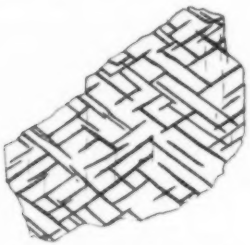


FIG. 1.—Peculiar perthite (½ natural size).

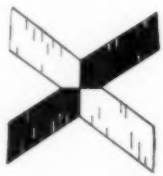


FIG. 2.—Albite from perthite (magnified).

a specimen with the basal cleavage close to the eye. A reflection being obtained from the microcline cleavage, on revolving the specimen about the *a*-axis a little toward one, there is a reflection from the albite plates parallel to the (110) face, and on revolving it a little in the opposite direction, there is a reflection from the albite plates parallel to the $(1\bar{1}0)$ face. In each case the reflection is from the basal {001} cleavage. The angle between the (001)

[1] This perthite, as well as the albite described in the next item, are evidently from pegmatites. See Kemp. *Trans. Am. Inst. Min. Eng.*, XXVI, 195 (1897).

face of the microcline and the (001) face of albite on each side is $3\frac{1}{2}°$ as measured with the simple reflection goniometer.

A microscopic examination confirms the above. A section parallel to the base {001} shows the gridiron structure for the microcline and plates of albite with extinction angles of about $3\frac{1}{2}°$. The albite plates parallel to the (110) face have extinction in the opposite direction from those parallel to the $(1\bar{1}0)$ face. Close examination reveals a few narrow twin lamellae in each set of albite plates. Fig. 2 is a diagrammatic drawing of a thin section cut parallel to (001).

The question arises as to whether this intergrowth can be called perthite or not. In the original perthite the albite plates are polysynthetically twinned and are parallel or approximately parallel to the *a*-axis. There is before me a specimen from the original locality, Perth, Canada (Fig. 3), which shows a coalescence of albite plates practically forming a plate parallel to the (110) face. I have also noted albite plates parallel to (110) in microcline-perthite from Rincon, Cal. On account of the gradation between the typical perthite and the peculiar perthite, it seems advisable to extend the term perthite to cover such cases. It should also be mentioned that normal perthite occurs among the Port Henry specimens. These specimens consist of microcline with plates of albite set parallel to the {100} face. They show polysynthetic albite twinning.

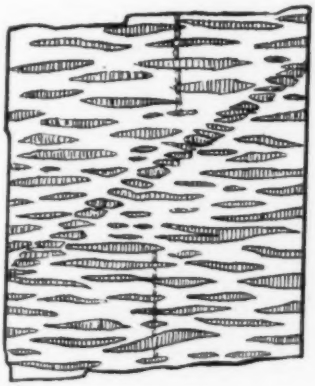


FIG. 3.—Perthite

ALBITE WITH BRACHYPINACOIDAL PARTING

Some cleavable albite of pale-green color from Port Henry, N.Y., consists of two kinds of specimens. Part of the specimens break in plates parallel to basal {010} cleavage while others break in plates parallel to the side pinacoid {010} and have a lamellar

structure. In albite the basal cleavage is perfect and the side pinacoidal cleavage, imperfect, hence the lamellar specimens are abnormal. A close examination of the two kinds of specimens shows polysynthetic twinning according to the albite law. In the basal cleavage of the first-mentioned variety the twinning lamellae are fairly uniform. Fig. 4 represents the basal cleavage of the variety with lamellar structure. Most of the twinning lamellae are very narrow, but every fifth to tenth one is much wider. On tracing the wider lamellae to the edge of the specimen there is usually noticed a parting plane. These parting planes are covered with a thin film of chlorite. In a specimen about 1 cm. wide there are about twenty-two broad lamellae and about twenty parting planes. The films of chlorite are probably the result, not the primary cause, of the parting, for the normal albite has finely divided chlorite all through it and not concentrated in films.

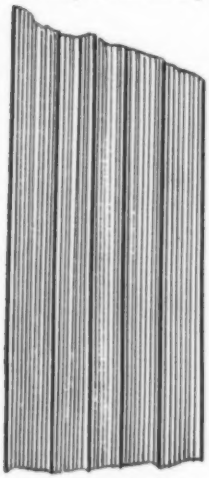


FIG. 4.—Albite twinning on albite (magnified).

If my observations are correct, there is both cleavage and parting in the same direction, namely, parallel to {010}. I know of no other similar case on record but there seems to be no reason why the same direction cannot be one of molecular disturbance as well as one of weak cohesion.

PERICLINE PARTING IN PLAGIOCLASE

Cleavable white plagioclase from Amelia Co., Va., shows a dull surface with bright spots. The bright spots are cleavage surfaces parallel to the base {001}. The dull surface is a plane of separation parallel to the rhombic section, for pericline twin lamellae are visible on the imperfect {010} cleavage. A glass slip was cemented on the dull surface and the angle between it and the cleavage measured with the reflecting goniometer. The angle is $+9°$, which places the plagioclase as albite-oligoclase, Ab_6An_1. Fig. 5 is a side elevation showing the cleavage, parting, and pericline twin lamellae.

I also have a specimen of albite from Auburn, Me., which shows pericline parting. The angle between the cleavage and the parting is $+13°$, as nearly as can be measured with a contact goniometer, which places it as about Ab_{12} An_1. In this specimen there is pericline twinning as well as albite twinning and good cleavage parallel to {001}, {110}, {1$\bar{1}$0}, and {010}. The mineral splits easily parallel to {010}, and hence there is both parting and cleavage parallel to this face. The extinction angle on the (010) face is about 20°.

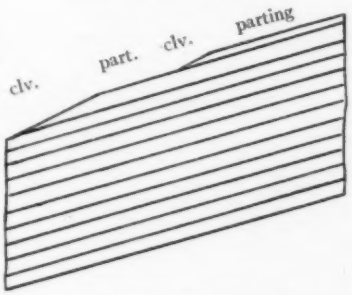


FIG. 5.—Albite-oligoclase, Ab_6An_1

Pericline parting was also noticed on a specimen of oligoclase from Bamle, Norway. A cover-glass was cemented to the dull parting surface and the angle between it and the cleavage was found to be $+3°$ 50′, measuring with the contact goniometer. This measurement places the feldspar as about Ab_3An_1, which is confirmed by the extinction angle of 0° on the (010) cleavage face.

For another plagioclase from Labrador, showing well-defined pericline twinning and only faint albite twinning, the cleavage and the parting are parallel, as nearly as can be judged. Even in this case there is lamellar structure due to pericline parting. According to Penfield and Sperry[1] the angle of the rhombic section for Ab_1An_1 is ±0°. This places the feldspar as andesine-labradorite, which is confirmed by the extinction angle of $-15°$ on (010).

PRISMATIC CLEAVAGE IN THE FELDSPARS

Labradorite from Labrador also occasionally shows dull surfaces due to pericline twinning. These dull surfaces are almost parallel to the cleavage, but careful measurement with the reflection goniometer proves the angle between the cleavage and the parting (using a cover-glass on the latter) to be about $-3°$ 40′

[1] *Am. Jour. Sci.*,(3) XXXIV, 390 (1887).

(average of 4° 5′ and 3° 15′). This proves the labradorite to be about $Ab_2\ An_3$. Fig. 6 is a side elevation of this labradorite.

The imperfect cleavage parallel to the unit form {110} or {110} and {1$\bar{1}$0} in the feldspars has not been sufficiently emphasized. It is present in nearly every specimen of the common feldspars which I have examined and is a valuable aid in orienting cleavages and imperfect crystals. Were it not for the prismatic cleavage, it would often be impossible to orient the feldspar and hence to determine the kind of feldspar. Even when not distinct, its intersection with (010) gives the direction of the *c*-axis.

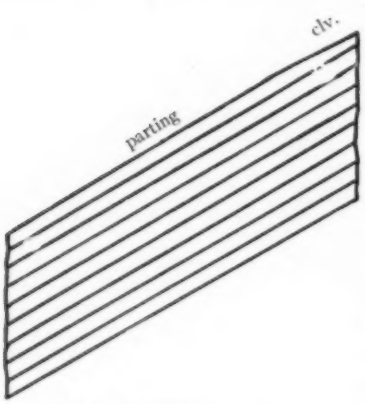


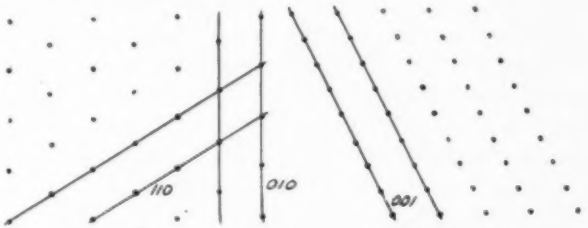
FIG. 6.—Labradorite, Ab_2An_3

That this plane of separation is cleavage and not parting is probable from a consideration of the internal structure of orthoclase. There are two possible space-lattices for monoclinic crystals, the monoclinic parallelepiped and the clinorhombic prism. The latter fits orthoclase better, as can be seen from Figs. 7*a* and 7*b*. According to Bravais, cleavage is parallel to the faces of greatest density, that is, those with molecules most closely packed. From the figures it can be seen that cleavage in orthoclase must be parallel to the {001}, {010}, and {110} forms, for the distance between adjacent rows of molecules is greatest for these directions.

The other feldspars evidently have almost the same structure as orthoclase. The separation parallel to the unit forms {110} and {1$\bar{1}$0} is cleavage rather than parting, though there may also be parting in the same direction in addition. Thus in the albite from Auburn, Me., and in oligoclase from New York City, the surfaces parallel to (110) and (1$\bar{1}$0) are coated with minute scales of sericite and the surfaces are rather dull.

SUMMARY

A peculiar intergrowth of microcline and albite is described. The albite plates are parallel to the unit prism faces. Plates parallel to (110) are in twinning position (albite twinning) with respect to the plates parallel to (1$\bar{1}$0). The term perthite may be extended to include any regular intergrowth of albite with orthoclase or microcline, either of the latter being in excess (antiperthite when albite is in excess).



7*a*—Plan 7*b*—Side elevation

FIG. 7.—The space-lattice of orthoclase

Lamellar albite with easy planes of separation parallel to the side pinacoid {010} are explained by a parting in this direction. Here we have cleavage and parting in the same direction, and the variation in the side pinacoidal cleavage often noted in the literature may thus be explained.

Several kinds of plagioclase varying from albite to labradorite, and including $Ab_{12}An_1$, Ab_6An_1, Ab_3An_1, Ab_1An_1, and Ab_2An_3, show parting parallel to the rhombic section due to polysynthetic pericline twinning. The surfaces are dull and make slight angles with the cleavage surfaces. In these specimens we have examples of parting which are not parallel to either actual or possible crystallographic faces. As far as I know similar cases have not been recorded.

The imperfect separation in the feldspars parallel to the (110) and (1$\bar{1}$0) faces is cleavage rather than parting. This cleavage is almost universally present and is of great assistance in orienting feldspar cleavages.

ROCK CLASSIFICATION ON THREE CO-ORDINATES[1]

ALEXANDER N. WINCHELL

There are many published classifications of igneous rocks, and their very number and variety are an indication of the difficulties inherent in the problem of constructing a satisfactory schematic arrangement—difficulties which are due largely to the fact that rocks are not chemical units, but mechanical mixtures, whose proportions may vary almost indefinitely in a great many ways.

It is generally admitted that at present the most satisfactory classifications are based upon, first, mineral (or chemical) composition, and, second, texture or geologic mode of occurrence. It is to be hoped that with advancing knowledge classifications may be based largely upon the principles of eutectics and the method of genesis of igneous types; at present the use of such conceptions as bases of classification may be recognized as desirable, but must be held in abeyance as impossible without more information.

A classification of igneous rocks based almost wholly upon chemical composition has been worked out in detail by Cross, Iddings, Pirsson, and Washington.[2] It has come into use gradually by an increasing number of petrologists, but its service to science is restricted by two facts: first, it commonly ignores the actual mineral composition in favor of an imaginary mineral composition known as the "norm," and, second, it cannot be used until the chemical composition[3] of the rock is known. Its great advantage lies in the fact that it reveals chemical characteristics and relationships with fidelity and clearness.

The classification of Rosenbusch,[4] which has been developed

[1] Published with the permission of the Director of the U.S. Geological Survey.

[2] *A Quantitative Classification of Igneous Rocks.* 1903.

[3] A microscopic determination of the quantitative mineral composition may be used as a substitute for a chemical analysis only when the norm and the mode are the same.

[4] *Elemente der Gesteinslehre.* 1910.

and modified by its author concurrently with the development of petrography during the past forty years, has come to have a very wide usage, either in its author's own form, or as modified by geologists in some respects to suit local needs. One of its elements of strength is the fact that it is based upon the mineral composition, and only secondarily defined in terms of chemical composition. It is also based upon the geological conditions of formation, so that the rocks of batholiths are separated from those of surface flows and both are separated from those of dikes and sills. Rosenbusch has never put this classification into diagrammatic form, and this fact has aided him in adapting it to advancing knowledge and enabled him to employ in some groups as minor bases of division factors or properties wholly inapplicable to other groups.

It is surprising that even in the latest form Rosenbusch still recognizes geological age as a basis of classification in some groups. He also emphasizes the important distinction between alkaline and other rocks.

In spite of its relative inflexibility a diagrammatic or tabular scheme of classification has numerous advantages, to which, for example, Kemp's[1] greatly simplified modification of the Rosenbusch classification owes much of its popularity. Such tabular schemes have heretofore been arranged on two co-ordinates. The relationships of rocks are so numerous and complicated that one of the chief defects of diagrammatic devices has been that they brought out so few of these affinities. By the use of transparent paper such a classification may be constructed on three co-ordinates as shown on the triple insert, and the advantages of such a scheme obtained without the defect mentioned. A classification on three co-ordinates does not show all the relationships that exist, but it exhibits many more than the ordinary arrangement, and it is believed that no more can be shown without sacrificing the advantages of the tabular arrangement.

The classification given herewith is based largely upon that of Rosenbusch, but it differs from the latter in various important respects, so that responsibility for it must lie with the author.

The first co-ordinate is in the direction normal to the paper, and

[1] *Handbook of Rocks.* 1906.

rocks belonging to a given series along this co-ordinate are placed within a single rectangle on successive sheets. For example, gabbro, essexite, and theralite form a series of this kind, the whole series to be observed simultaneously by looking through transparent paper for the second and third members. Along this co-ordinate igneous rocks are classified as normal or alkali-calcic (conveniently abbreviated to alkalcic), alkaline, and peralkaline.

Subsiliceous alkalcic rocks are characterized mineralogically by the absence of feldspars and feldspathoids and the presence of biotite, olivine, ferromagnesian (or mafic[1]), or calcareous-ferromagnesian (or calmafic), amphibole or pyroxene (or two or more of these). They are distinguished chemically by very low content of alkalies and alumina and high tenor of magnesia, lime, and iron. Mediosiliceous alkalcic rocks are characterized mineralogically by the presence of soda-lime feldspar nearly or wholly to the exclusion of alkali feldspar, and by the presence of biotite, olivine, mafic, or calmafic amphibole or pyroxene; they contain more soda than potassa (K_2O) and more than enough alumina to saturate the alkalies. Persiliceous alkalcic rocks are marked by the presence of soda-lime feldspar with dominant alkali feldspar, and with muscovite, biotite, or mafic or calmafic amphibole or pyroxene; chemically they are distinguished by the presence of both alkalies and lime with more than enough alumina to saturate the alkalies.

In general, alkalcic rocks are characterized by the presence of soda-lime feldspar (or no feldspar) with mica, olivine, mafic or calmafic amphibole or pyroxene, and the absence of feldspathoids (or lenads), soda-amphiboles, soda-pyroxenes, and lithia micas; they contain both alkalies and lime with more than enough alumina to saturate the alkalies.

Subsiliceous alkaline rocks are distinguished mineralogically by the absence of feldspars and lenads, and the presence of sodic and titaniferous amphiboles and pyroxenes; chemically they contain little alumina, and relatively large amounts of alkalies, titanic acid,

[1] The new terms felsic and mafic are here used in accordance with the proposal of Cross, Iddings, Pirsson, and Washington, *Jour. Geol.* XX (1912), p. 560, as short general terms, the first applying to feldspathic minerals and quartz, or rocks rich in such minerals, the second applying to all ferromagnesian minerals or rocks rich in such minerals.

and (often) ferric iron. Mediosiliceous alkaline rocks contain calcic plagioclase and a little lenad or alkali feldspar, and micas or soda-amphiboles or soda-pyroxenes; or they contain acid soda-lime feldspar with equal alkali feldspar and with micas, pyroxenes, amphiboles; chemically they contain in the first case high alkalies, lime, and titanic acid and low magnesia and silica, and in the second case high alkalies with potassa equal or dominant over soda, and abundant lime and alumina. Persiliceous alkaline rocks are characterized by dominant alkali feldspars, no soda-lime feldspar nor lenad, and lithia-mica, soda-amphibole, soda-pyroxene; they are very rich in alkalies and rarely in ferric iron, and very poor in lime and magnesia, and contain insufficient alumina to saturate the alkalies.

In general, alkaline igneous rocks contain sodic mafic silicates and no feldspar, or they contain more alkali feldspar and less soda-lime feldspar than the corresponding alkalcic rocks; chemically they contain more alkalies and less lime than the latter.

Peralkaline rocks are characterized mineralogically by the presence of feldspathoids (or lenads); they commonly contain also soda-pyroxene or soda-amphibole, or both. Chemically they are distinguished by insufficient silica to combine with the abundant alkalies to form feldspars after saturation of other available bases as orthosilicates.

In addition to the alkalcic, the alkaline, and the peralkaline, other divisions might be recognized, for example, the superalkaline, in which feldspars are entirely replaced by lenads. But this division consists of rocks which are very rare, and therefore it may be conveniently regarded as merely an extreme variation of peralkaline rocks. In spite of their rarity many names have been proposed for superalkaline rocks. Thus, by loss of feldspar, nepheline syenite becomes urtite, nepheline porphyry becomes sussexite, phonolite becomes leucitophyre, theralite changes to fergusite, tephrite to nephelinite or leucitite, olivine theralite to missourite, basanite to nepheline basalt or leucite basalt, and the volcanic equivalent of teschenite to analcite basalt. Another division might consist of the subsiliceous or lamprophyric rocks; but, with rare exceptions, such as shonkinite, the lamprophyric rocks are related

closely to gabbro, peridotite, or basalt, or their alkaline equivalents, and may be regarded as variations of such types.

The second co-ordinate extends from left to right across the paper and relates to mode of occurrence and conditions of formation; here again three classes are established, namely, plutonic, hypabyssal, and volcanic. Plutonic rocks solidified at considerable depth and have been later uncovered and brought to view through erosion. They form batholiths, stocks, and laccoliths. Hypabyssal rocks crystallized at moderate depth in the form of dikes, sills, or intrusions of irregular shape called chonoliths;[1] they are often called dike rocks. Volcanic rocks were brought to the surface (or near it) by volcanic action and form surface flows or intrusions near the surface. They also form beds and irregular aggregates through the accumulation of fragmental materials thrown out of volcanoes.

Plutonic rocks have granitic texture, that is, the essential constituents are crystalline anhedra of irregular shape and similar sizes, or dissimilar sizes showing gradations without a break from the smallest to the largest. Hypabyssal rocks may be divided into three types: the felsic, the aschistic, and the mafic. The aschistic or undifferentiated hypabyssal rocks commonly have porphyritic texture with abundant large phenocrysts and coarse granitic or aplitic groundmass. The felsic and mafic hypabyssal rocks commonly have aplitic texture, that is, they consist chiefly of fine evenly granular euhedral constituents, wholly crystalline. Some of these rocks have pegmatitic texture; others have porphyritic texture. The volcanic rocks commonly have glassy, felsitic, trachytic, or porphyritic textures; certain types have ophitic texture, in which the plagioclase feldspars in lath-shaped crystals are partly or wholly inclosed by mafic minerals.

The third co-ordinate extends from top to bottom of the sheet and relates to mineral composition; on this basis igneous rocks are divided into three primary groups: first, those in which alkali feldspar is dominant or in which felsic minerals including lenads are dominant, second, those in which soda-lime feldspar is equal to or dominant over alkali feldspar, or mafic minerals are equal to or

[1] R. A. Daly, *Jour. Geol.*, XIII (1905), 498.

dominant over felsic minerals including lenads, and, third, those containing no essential feldspar nor feldspathoid. Subdivisions are based largely upon quartz and olivine, since these minerals serve to measure the relative amount of silica present—the presence of quartz or the absence of olivine indicating a higher relative silication than the reverse condition.

It may be desirable to state explicitly that there are igneous rocks which will not readily find a place in this classification just as there are rocks which do not fit each other classification. Such a condition must exist, since rocks exhibit all sorts of gradations from one type to another, and classifications, on the other hand, establish sharply separated categories. A few illustrations will serve to emphasize this fact.

Rocks are classified as plutonic, hypabyssal, and volcanic, depending chiefly upon the depth at which they consolidate. But it is clear that there is a complete gradation in depth from the surface to the greatest depths open to observation. Similarly there is a gradation in the rocks formed at various depths. Hypabyssal rocks are found in dikes (or sills) consolidated at moderate depths. The same dikes may contain plutonic rocks at greater depths and volcanic rocks near the surface. Only those dike rocks which differ in some recognizable way from the plutonic and volcanic rocks are included as hypabyssal rocks.

Again, rocks are classified as alkalcic and alkaline. But there are many gradations from one type to the other. Granodiorite is an intermediate group of considerable importance. Assuming a total feldspar tenor of 60 per cent, Lindgren[1] has defined tonalite (or quartz diorite), as containing less than 8 per cent of alkali feldspar, granodiorite as containing 8–20 per cent of alkali feldspar, quartz monzonite, as containing 20–40 per cent of alkali feldspar, and granite as containing more than 40 per cent. The percentage of alkali feldspar cannot be accurately determined from an analysis of the rock because potassa (K_2O) may enter the plagioclase and soda may enter the orthoclase; it should be obtained by direct microscopic measurements. Granodiorite is intermediate between tonalite and quartz monzonite, and is therefore one of many con-

[1] W. Lindgren, *Amer. Jour. Science*, IX (1900), 269.

necting links between alkalcic and alkaline rocks. It is especially important because it constitutes large intrusions in California and elsewhere.

The volcanic equivalent of granodiorite, which may be appropriately called rhyodacite, forms another intermediate group between the alkalcic and the alkaline rocks. Having no distinctive name available, rhyodacites have been classed with dacites in the past; the two groups differ as distinctly as tonalite and granodiorite. It is because the rhyodacites and even some quartz latites have been described as dacites in the past that Daly[1] finds the average composition of dacite corresponding to that of granodiorite rather than tonalite. As may be seen from the tables of average composition of igneous rocks on pp. 217–221, dacite, like all the volcanic rocks, is more siliceous than the corresponding plutonic rock, tonalite, but is nevertheless its equivalent, as indicated especially by the tenor of alkalies. Similarly rhyodacite and granodiorite are related.

A rock which contains more ferromagnesian minerals (and less silica) than granite, but is nevertheless characterized by dominant alkali feldspar and quartz with subordinate plagioclase, has been called quartz syenite by Brogger.[2] It is sometimes regarded as intermediate between syenite and granite. But it is an alkaline and not an alkalcic rock type, and is very closely associated with quartz monzonite in the field. It should be regarded as a potassic variation from quartz monzonite, and not as a type closely related to granite. It is surprising to find that the average quartz syenite is less siliceous than the average quartz monzonite. This may be due to a tendency to classify the more siliceous quartz syenites as granites.

The relative depth at which rocks crystallized is estimated commonly by a study of their texture. Thus, plutonic rocks have granitic texture, volcanic rocks usually have felsitic or porphyritic texture; and textures are independent of mineral composition. But the ophitic texture, characterized[3] by the crystallization of

[1] R. A. Daly, *Proc. Amer. Acad.*, XLV (1910), 239.

[2] W. C. Brogger, *Zt. Kryst.*, XVI (1890), 81.

[3] A. N. Winchell, *Bull. Geol. Soc. Amer.*, XX (1908), 661.

plagioclase feldspars in lath-shaped forms before the solidification of the ferromagnesian minerals, is unknown in siliceous and ultrabasic rocks, and it is found in rocks crystallizing at moderate depth as well as in volcanic rocks. Independent of all other considerations, rocks having the ophitic texture are called diabase; they may occur in dikes or sills crystallizing at moderate depths, or they may be found in surface flows. Diabase proper has the mineral composition of augite andesite (or auganite); olivine diabase has the composition of basalt containing monoclinic pyroxene; quartz diabase and hypersthene diabase are also known.

The nomenclature employed is for the most part entirely familiar to petrographers. No distinction based on geological age is recognized; therefore such terms as melaphyre and quartz porphyrite are excluded. In designating the aschistic hypabyssal rocks the term porphyry is used (even for plagioclastic types) in preference to porphyrite. For the alkalcic plutonic and volcanic rocks it is believed that compound names like quartz diorite and augite andesite are objectionable, and should be replaced by simpler designations. Therefore, Spurr's[1] proposal to use tonalite in place of quartz diorite is adopted; and it is proposed to abbreviate augite andesite to the simple and almost self-explanatory form auganite.[2] Auganite proper is a volcanic rock consisting essentially of calcic plagioclase and augite; other varieties include hornblende auganite, related to andesite, and hypersthene auganite, which contains plagioclase and orthorhombic pyroxene with or without augite. A true augite andesite is a volcanic rock consisting essentially of sodic plagioclase (andesine or oligoclase) and augite.

That auganite deserves a distinctive name and is not merely a variety of andesite, as suggested by the name augite andesite, is well shown by field relations such as those existing at National, Nevada, where the important rocks are rhyolite, andesite, and auganite. At this locality the auganite and andesite are of wholly different age and wholly different appearance. The auganite might be confused with basalt without close examination, since it

[1] J. E. Spurr, *Amer. Geol.*, XXV (1900), 210, 232; *U.S. Geol. Surv. 20th Ann. Rpt.*, VII (1900), 188, 190.

[2] A. N. Winchell, *Mg. and Sci. Press*, November 22, 1912.

is black and dense; but its separation from the andesite is accomplished at a glance when both rocks are fresh.

A substitute for the compound name olivine gabbro is desirable but is not here suggested.

The average composition of each type of igneous rock should be available for comparison with the composition of rocks at given localities. Daly[1] has prepared tables giving these averages for certain rock types; in the following tables these have been supplemented by averages computed by the author.

In the tables of average composition, numbers 1, 4–7, 10, 13, 16, 19, 21, 23, 25, 26, 31–34, 36, 38, 40, 49–52, 54–57 were calculated by Daly;[2] the others have been prepared from data published by Rosenbusch (*Elemente der Gesteinslehre*, 3d edition, Stuttgart, 1910), and by Clarke (*U.S.G.S. Bulletin 419*, 1910), with the following exceptions. No. 3 is based on data of Rosenbusch (*loc. cit.*), Clarke (*loc. cit.*), and Osann (*Chemische Petrographie*, II, 1905). No. 9 is from data of Rosenbusch (*loc. cit.*), Clarke (*loc. cit.*), Osann (*loc. cit.*), and Weidmann (*Wis. Surv. Bull. XVI*, 1907). No. 14 is based on data of Rosenbusch (*loc. cit.*), Washington (*Jour. Geol.*, VII [1899], 57), and Ogilvie (*Jour. Geol.*, XVI [1908], 285). No. 15 is based on data of Rosenbusch (*loc. cit.*) and Osann (*loc. cit.*). No. 17 is from data of Rosenbusch (*loc. cit.*), Lacroix ("Minéralogie de Madagascar," *Nouv. Arch. Muséum*, I [1903], 30, 194), and Young (*Geol. Surv. Canada*, XVI, H, 1906). No. 27 is from data of Rosenbusch (*loc. cit.*) and Hore (*Econ. Geol.*, VI [1911], 54). No. 29 is from data of Rosenbusch (*loc. cit.*) and Doelter (*Akad. Wiss. Wien*, CXI, I [1902], 980). No. 37 includes 12 quartz keratophyres (Daly), 13 pantellerites (data of Rosenbusch), and 6 comendites (data of Rosenbusch). No. 44 is from data of Daly (*loc. cit.*), Clarke (*loc. cit.*), Rosenbusch (*loc. cit.*), and Osann (*loc. cit.*), auganites excluded. No. 47 is from data of Clarke (*loc. cit.*), Rosenbusch (*loc. cit.*), and Osann (*loc. cit.*), rocks containing acid plagioclase or orthoclase being excluded.

[1] R. A. Daly, *Proc. Amer. Acad.*, XLV (1910), 211.

[2] *Loc. cit.*

AVERAGE COMPOSITION OF PLUTONIC ROCKS

	1 Granite	2 Alkali-granite	3 Syenite	4 Alkali-syenite	5 Nepheline Syenite	6 Tonalite	7 Granodi-orite	8 Quartz Monzonite	9 Quartz Syenite	10 Diorite	11 Monzonite	12 Nepheline Monzonite
No. of analyses.....	236	10	13	23	43	20	12	25	18	70	10	1
SiO_2.....	69.92	72.70	58.06	61.99	54.63	59.47	55.10	65.78	62.34	56.77	55.31	46.40
Al_2O_3.....	14.78	12.12	16.25	17.93	19.89	16.52	15.82	15.71	15.06	16.67	15.91	21.60
Fe_2O_3.....	1.62	2.28	4.18	2.22	3.37	2.63	1.64	1.83	2.32	3.16	3.25	4.07
FeO.....	1.67	1.44	3.48	2.29	2.20	4.11	2.66	2.22	3.02	4.40	4.02	4.95
MgO.....	.97	.32	2.52	.96	.87	3.75	2.17	1.57	2.76	4.17	4.33	2.75
CaO.....	2.15*	.49	4.06†	2.55	2.51	6.24	4.66	3.76	3.98‡	6.74	6.86	8.44
Na_2O.....	3.28	5.42	3.67	5.54	8.26	2.98	3.82	3.35	3.56	3.39	3.73	6.29
K_2O.....	4.07	4.20	5.16	4.98	5.46	1.93	2.29	3.80	4.68	2.12	4.18	2.71
H_2O.....	.78	.82	1.37	.76	1.35	1.39	1.09	1.17	1.09	1.36	.67	1.25
TiO_2.....	.39	.09	.63	.56	.86	.64	.54	.53	.74	.84	.73	1.57
P_2O_5.....	.24	.12	.39	.14	.25	.26	.16	.18	.21	.25	.46	.26
MnO.....	.13	.....	.23	.08	.35	.08	.05	.10	.24	.13	.11	.....
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.29

* Includes 0.02 SrO and 0.06 BaO. † Includes 0.11 SrO and 0.15 BaO. ‡ Includes 0.10 SrO and 0.34 BaO.

AVERAGE COMPOSITION OF PLUTONIC ROCKS—*Continued*

	13 Gabbro	14 Essexite	15 Theralite	16 Olivine Gabbro	17 Olivine Essexite	18 Olivine Theralite	19 Pyroxenite	20 Alkali-pyroxenite	21 Peridotite	22 Alkali-peridotite	
No. of analyses	24	6	4	17	6	2	4	3	49	1	
SiO_2	49.50	49.92	48.95	46.49	46.44	41.45	49.82	44.30	44.39	28.15	.....
Al_2O_3	18.00	18.59	15.45	17.73	19.27	14.94	5.12	8.93	5.14	2.30	.....
Fe_2O_3	2.80	4.19	3.97	3.66	3.85	7.76	1.83	7.94	3.88	21.61	.....
FeO	5.80	5.01	4.63	6.17	6.02	7.72	7.44	7.75	6.70	15.93	.....
MgO	6.62	2.66	5.24	8.86	4.33	6.11	19.55	10.29	29.17	20.67	.....
CaO	10.64	7.32	10.70	11.48	8.65	10.44	13.00	15.28	6.13	3.45	.....
Na_2O	2.82	5.67	4.30	2.16	4.90	5.69	.37	.74	.64	.63	.....
K_2O	.98	3.05	2.29	.78	2.34	2.42	.21	1.05	.76	.29	.....
H_2O	1.60	.91	2.21	1.04	1.18	1.51	1.06	1.18	1.80	3.45	.....
TiO_2	.84	1.76	1.52	1.17	2.10	1.61	1.46	2.31	.88	2.55	.....
P_2O_5	.28	.80	.47	.29	.81	.35	.05	Tr.	.14	Tr.	.....
MnO	.12	.22	.17	.17	.11	.....	.09	.23	.19	.45	.....
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.98	100.00	.....

AVERAGE COMPOSITION OF HYPABYSSAL ROCKS

	Felsic Types								Mafic Types				
	23 Aplite	24 Alkali-aplite	25 Bostonite	26 Tinguaite	27 Plagi-aplite	28 Malchite	29 Allochetite	30 Beerbachite	31 Minette	32 Kersantite	33 Camptonite	34 Fourchite (and Monchiquite)	35 Garewaite
No. of analyses	15	6	5	15	10	6	2	1	10	20	15	16	1
SiO_2	75.00	74.40	61.32	55.02	68.75	60.18	50.19	47.21	49.45	50.79	40.70	45.17	42.84
Al_2O_3	13.14	13.11	18.43	20.42	16.36	17.81	22.40	20.52	14.41	15.26	16.02	14.78	4.60
Fe_2O_3	.58	.96	3.84	3.06	.78	1.38	3.03	7.48	3.39	3.29	5.43	5.10	5.69
FeO	.40	1.10	1.60	1.82	1.57	4.21	3.60	5.32	5.01	5.54	7.84	5.05	8.48
MgO	.30	.07	.46	.59	.63	2.92	1.95	4.16	8.26	6.33	5.43	6.26	24.60
CaO	1.13	.30	1.45	1.67	2.60	5.37	5.26	8.63	6.73	5.73	9.36	11.06	11.41
Na_2O	3.54	4.55	5.75	8.63	7.24	4.14	6.85	5.17	2.54	3.12	3.23	3.69	.61
K_2O	4.80	5.12	4.94	5.38	.68	2.56	3.40	.33	4.69	2.79	1.76	2.73	.42
H_2O	.71	.21	1.31	2.77	1.06	.65	2.46	.34	3.04*	5.71†	5.59‡	3.40	1.80
TiO_2	.30	.18	.89	.36	.28	.42	.86	.....	1.23	1.02	3.86	1.90	.....
P_2O_5	.05	Tr.	.....	.06	.05	.17	.....	.46	1.12	.35	.62	.51	.....
MnO	.07	Tr.	.01	.22	Tr.	.19	.....	.....	.13	.05	.16	.35	Tr.
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.91	100.00	100.00	100.00	100.00	100.45

* Includes 0.61 CO_2. † Includes 2.61 CO_2. ‡ Includes 2.97 CO_2.

AVERAGE COMPOSITION OF VOLCANIC ROCKS

	36 Rhyolite	37 Alkali-rhyolite	38 Trachyte	39 Alkali-trachyte	40 Phonolite	41 Dacite	42 Rhyodacite	43 Quartz Latite	44 Andesite	45 Latite	46 Latite-Phonolite
No. of analyses. .	64	31	48	17	25	16	16	6	57	18	6
SiO_2.	72.60	72.72	60.68	62.46	57.45	65.86	67.67	65.81	61.30	57.93	56.82
Al_2O_3.	13.88	11.68	17.74	17.13	20.60	15.64	15.62	16.72	16.88	17.05	19.09
Fe_2O_3.	1.43	3.09	2.64	2.89	2.35	2.56	2.00	3.10	3.01	3.88	2.81
FeO.	.82	1.43	2.62	1.92	1.03	1.70	1.25	.55	2.76	2.66	2.06
MgO.	.38	.35	1.12	.53	.30	1.71	.76	.66	2.49	2.13	1.19
CaO.	1.32	.80	3.09	1.43	1.50	4.24	2.56	2.88	5.07	5.16*	4.10
Na_2O.	3.54	5.66	4.43	6.30	8.84	3.93	4.10	3.73	3.99	4.19	6.67
K_2O.	4.03	3.10	5.74	5.36	5.23	1.90	3.73	4.28	1.89	4.13	4.79
H_2O.	1.52	.62	1.26	.97	2.04	1.77	1.61	1.52	1.33	1.52	1.18
TiO_2.	.30	.23	.38	.01	.41	.47	.48	.43	.86	.87	.84
P_2O_5.	.06	.08	.24	.15	.12	.14	.15	.17	.25	.40	.30
MnO.	.12	.24	.06	.25	.13	.08	.07	.15	.17	.08	.15
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* Includes 0.15 BaO.

AVERAGE COMPOSITION OF VOLCANIC ROCKS—*Continued*

	47 Auganite	48 Trachy-dolerite	49 Tephrite	50 Diabase	51 Olivine Diabase	52 Basalt	53 Olivine Trachy-dolerite	54 Basanite	55 Augitite	56 Picrite	57 Limburgite
No. of analyses..	73	10	24	20	17	161	27	16	6	3	7
SiO_2.....	54.97	50.93	49.14	50.12	50.10	48.78	48.74	44.20	42.25	43.24	41.69
Al_2O_3.....	16.69	19.06	16.57	15.68	14.43	15.85	16.41	15.64	16.26	15.19	14.80
Fe_2O_3.....	3.94	4.49	3.65	4.55	5.06	5.37	4.62	4.35	8.43	8.62	15.04
FeO.....	4.75	3.88	6.68	6.73	6.31	6.34	6.26	6.14	5.46	7.89	
MgO.....	4.13	2.72	3.98	5.85	7.32	6.03	4.29	8.89	5.49	8.56	8.64
CaO.....	8.02	7.04	9.88	8.80	9.53	8.91	8.06	9.74	9.75	13.78	11.98
Na_2O.....	3.19	4.91	2.57	2.95	2.75	3.18	4.08	4.03	4.45	.54	3.52
K_2O.....	1.45	3.47	3.39	1.38	.73	1.68	2.83	1.83	1.92	.48	1.17
H_2O.....	1.39	1.80	2.00	1.93	2.00	1.76	1.77	2.67	2.43	1.21	2.36
TiO_2.....	.89	.74	1.00	1.41	1.25	1.39	1.85	1.64	2.52	.....	.67
P_2O_5.....	.28	.65	.84	.37	.27	.47	.80	.68	1.04	.49	.13
MnO.....	.30	.31	.30	.23	.25	.29	.29	.19	.....	.....	.....
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

It should be remembered that rock names are not always used with the same meaning; therefore some of the averages presented herewith include analyses of rocks not classified in accordance with recent practice; this is especially true of the average for granite, which certainly includes some analyses of rocks which would now be classified as quartz monzonite, and probably includes also a few alkaligranites. The average for basalt probably includes analyses of trachydolerites. It is to be hoped that averages for these rocks will be prepared from analyses of rocks whose correct classification cannot be questioned.

If the average quantitative mineral composition of the various igneous rocks were known, it would be as useful as the average chemical composition. Of course the "normative mineral composition" can be calculated directly from the average chemical composition for each rock type. But the "normative mineral composition" is much less important than the "modal" mineral composition; it is merely the result of a distribution of the oxides among a certain group of minerals somewhat arbitrarily selected. In a few cases the actual (modal) mineral composition can be calculated at least approximately from the chemical composition. As our knowledge of the composition of the mineral constituents of each rock type increases, the mineral composition can be calculated for an increasing number of rocks.

A few calculations of this kind have been made; they are much facilitated by the use of Mead's circular slide rule.[1] For the alkaligranite all the ferric iron is assigned to riebeckite; alkaligranites often have, in place of riebeckite, either arfvedsonite, acmite, barkevikite, lithia mica, or two or three of these minerals. All the magnesia of the quartz monzonite is assigned to biotite and hornblende (including augite) in the ratio (about 3 to 1) required to prevent surplus of either lime or alumina in forming feldspars. The biotite and hornblende are assumed to have the composition obtained by analysis of those minerals from quartz monzonite from California (analysis *d*, Table XIV, and *a*, Table XIII, *Quant. Class. Ign. Rocks*). In calculating the mineral composition of the monzonite sufficient magnesia is assigned to biotite and hornblende to prevent

[1] W. J. Mead, *Econ. Geol.*, VII (1912), 136.

either an excess or a deficiency of silica in forming pyroxene. The biotite and hornblende are assumed to have the composition obtained by analysis of such minerals from monzonite (analysis *c*, Table XIV, and *b*, Table XIII, *Quant. Class. Ign. Rocks*).

As a preliminary, it is necessary to calculate the mineral composition in terms of the theoretical feldspar molecules; these may be changed into the feldspars actually present as follows. The feldspar of alkaligranite is either anorthoclase or perthitic albite with microcline or orthoclase. The second condition needs no further calculation; the first condition is obtained by simply combining the calculated orthoclase and albite. Andesine is the commonest plagioclase of quartz monzonite and monzonite; assigning to it the formula Ab_3An_2 the calculation results as follows:

APPROXIMATE AVERAGE MINERAL COMPOSITION OF ALKALI-GRANITE, QUARTZ MONZONITE, AND MONZONITE

	1 Alkaligranite	2 Quartz Monzonite	3 Monzonite
Quartz	24.7	23.7	....
Orthoclase	24.7	....	....
Albite	38.7	....	....
Soda-orthoclase	....	24.4	33.9
Andesine Ab_3An_2	....	36.2	34.0
Riebeckite	8.5	....	....
Ferriferous diopside	2.1	....	....
Pyroxene	....	3.1	18.8
Hornblende	....		3.2
Biotite	....	9.1	2.5
Magnetite	....	1.8	4.3
Ilmenite	0.2	....	....
Titanite	....	0.6	1.4
Apatite	0.3	0.4	1.1
(Water)	0.8	0.7	0.8
	100.00	100.00	100.00

THE OLD EROSION SURFACE IN IDAHO

A REPLY

JOSEPH B. UMPLEBY[1]

In a recent issue of this *Journal*[2] Mr. Eliot Blackwelder criticizes adversely the chain of reasoning that led me to the conclusion that the old erosion surface in Idaho is of Eocene age. To him the evidence seems to point to a much younger age, "probably post-middle-Miocene"—an inference which I believe to be incompatible with observed facts.

To account for the valleys now filled in many places with lavas, lake beds, and fluviatile deposits principally of Miocene age, Mr. Blackwelder suggests three possible explanations.

> One method is the deposition of the sediments in the bottoms of the valleys, in essentially their present state, as suggested in the [original] article. Again where weak materials have been down-folded or down-faulted between masses of harder rocks, they may be eroded to a lowland on account of differences of resistance to denuding processes. A third hypothesis is that the broad valleys occupied by the sediments were excavated and filled before the peneplain was made.

I shall endeavor to show that the first hypothesis only accords with field evidence. The second hypothesis is inadmissible because the old valleys constitute branching systems with members lying athwart the structure axes of the region. To derive all of these valleys by faulting would be to assume a complexity of fault systems in no wise borne out by field observations. Again, some of the lakes of Miocene age, as shown by fossil plants, present shore lines at elevations 2,800 feet beneath the plateau surface, so that even if down-faulting could be admitted the valleys in which the lakes existed must have been blocked out prior to the lacustrine epoch and hence prior to the Miocene. Therefore if the plateau

[1] Published with the permission of the Director of the United States Geological Survey.

[2] *Jour. Geol.*, XX, No. 5 (1912), 410–14.

surface is a product of planation it must antedate the existence of such Miocene lakes.

Still another line of evidence against the down-faulting or down-folding hypothesis is the direct observation from numerous exposures that folding or faulting is rare along the margins of the old valleys. In many places present-day streams have cut vertically from 1,000 to 3,000 feet or more into the lavas and tuffs which occupy the old valleys and thus afford excellent cross-sections of the earlier drainage channels. In the many sections of this kind which were examined, only one (near Junction, Lemhi County, and here the fault is post-Miocene) showed evidence of faulting and none presented down-folding The eruptive rocks or lake beds, usually in a nearly horizontal position, abut the older formations irrespective of their attitude and in many places the lavas contain fragmental material, clearly picked up from the surface over which they flowed. Furthermore, the slope of the contact in every place observed is toward the lava area.

The third hypothesis, which supposes that the valleys antedate the old erosion surface, is controverted by the shore-line relations already referred to. If the valleys were developed *before* the elevation of the old surface of gentle topographic forms, we are led directly to the conclusion that within the area planated the upper 2,800 feet of some of the old valleys remained unfilled throughout the period of that planation. Would not those portions below base-level have been filled, and that, early in the period of reduction?

The third hypothesis is also untenable in view of the inequal depth of the lavas along certain of the old valleys. Take, for instance, the one which extends from near Salmon City, via Prairie Basin, Rabbitfoot, Custer, and Stanley Basin, to the Snake River plains at Camas Prairie. Prairie Basin, about 1,000 feet below the plateau level, Stanley Basin, about 2,500 feet below it, and Camas Prairie, yet lower, represent unfilled segments of this old valley, while intermediate sections are flooded with lavas which in places, as at Twin Peaks in Parker Mountain mining district and at Estes Mountain near Custer, rise a few hundred feet above the plateau level.

Furthermore, the third hypothesis is untenable because of the topography along certain of the present-day streams. Salmon River heads in the Stanley Basin segment of the old valley above mentioned but near Stanley leaves it and enters a canyon so narrow that there is scarcely room for a wagon road. This gorge continues to a point near Challis, a distance of about 50 miles, where the stream emerges into a broad, open depression. Fifteen miles below Challis the river enters another narrow canyon which it follows for about 30 miles to a point near Salmon City, and, after flowing for 20 miles through a third broad valley, again enters a gorge which it follows nearly to the western border of the state. These open stretches along the course of Salmon River cannot be explained by local structure or by differences of resistance to denuding processes. Their distribution and individual outline are readily interpreted, however, if we consider them to be parts of the older valley system. The general depression about Challis has its greatest elongation almost at right angles to the course of Salmon River, but is itself continuous with an old valley, now filled in many places with eruptive rocks, which drained off to the southeast and joined the Snake River plains near Martin. The open stretch about Salmon City presents numerous exposures of plant-bearing Miocene lake beds which extend off to the southeast along the present course of Lemhi River and Birch Creek. To an observer in the field it is very clear that these open stretches date back to the earlier topography and that, though in part filled with Miocene lavas and sediments, they have persisted as great depressions throughout their entire history.[1] Salmon River has crossed them by headward erosion.

In the preceding paragraphs I have endeavored to show (1) that the old valleys were not developed by down-folding or down-faulting and (2) that they were not excavated prior to the planation of the region. The remaining hypothesis holds that the valleys are the product of erosion and were developed after the elevation of the old

[1] During the past three field seasons many notes have been made on the old valleys of southeastern Idaho north of Snake River, and several hundred miles of their courses have been sketched. It is expected to assemble this information in a later paper.

erosion surface. This is the view which I advanced in my original paper and to which I still subscribe.

The inequal filling of the old valleys, their branching systems with members athwart the structure axes of the region, their cross-sections, the absence of particular folding or faulting along their margins, the shore-line relations of the lakes which occupied some of them in Miocene times, the open stretches along the present drainage lines—all these features stand opposed to the second and third hypotheses but at the same time strongly support the first one.

The constructive part of Mr. Blackwelder's criticism is based on the third hypothesis; namely, that the old valleys, now in part filled with Miocene deposits, were formed *before* the period of profound degradation which resulted in the old erosion surface of Idaho. The fact that in many of the valleys the filling material never accumulated to within many hundreds of feet (2,800 feet at Salmon City and Gilmore) of the present plateau surface, is not easy to explain on the basis of this assumption. Widely distributed, deep depressions could not have persisted within the area during the period of its reduction to gentle topographic forms.

Mr. Blackwelder also objects to my belief that the old valleys were formed during the Oligocene epoch. I am well aware of the uncertainties involved in "allowing a geologic period for a process of unknown time requirements," but it does seem that in this case time requirements are as well known as is the duration of the geologic period involved. The coincidence of the Oligocene epoch with the development of the old valleys is not considered as an essential part of the constructive argument in my former paper, but is rather a corroborative bit of evidence. A considerable time must have been consumed in the development of these great valleys, especially so since they lie far within the plateau area. If the drainage was westward, as is suggested in a later paragraph, the streams must have worked headward, at least across the state of Idaho. This follows from the fact that the plateau is continuous to near the western border of the state. Limits are placed on the period of valley development on the one hand by the Miocene deposits which occupy them, and on the other by the old erosion

surface, thought to be of Eocene age because of its relation to surrounding Eocene sediments. The closing stages of the Eocene may have been involved in the development of the old valleys, although I do not think so, but that erosion continued locally within them on into the Miocene and somewhat intermittently, even down to the present, is attested by abundant evidence. Such facts and possibilities, however, do not appear to me to affect the conclusion that the old valleys, here filled and there partially filled, are parts of a drainage system which should be considered as Oligocene.

The latter part of Mr. Blackwelder's paper is devoted to an effort to show that the old erosion surface "is much younger than Eocene and probably post-middle-Miocene." In the earlier part of this reply I have emphasized the fact that the deep erosion valleys were locally never filled by many hundreds of feet with Miocene or other lavas or sediments, and hence could not have been formed until after the old surface of gentle topographic forms had been developed, and not until after it was elevated at least well toward its present position. The hypothesis that the valleys were developed prior to the planation of the region necessitates that they persisted throughout the period of that planation and at its close remained as open trenches, some of them 2,800 feet deep, in an area which approached closely the base-level of erosion for the region.

Mr. Blackwelder's principal evidence for his contention that the old surface is of late Miocene age is the general folding which the Miocene deposits of the region have undergone—a folding which he argues would have destroyed the evenness of the plateau surface. The folding of the lacustrine deposits has been brought to my attention by numerous exposures in Lemhi and Custer counties. About Salmon City the lake beds, which, from their thin-bedding, must have been laid down in a relatively horizontal position, are now inclined in various directions, in most places at angles of about 10 degrees, but locally they dip as steeply as 25 degrees. It is noteworthy, however, that the dips, in every instance where I have observed them, change direction within short distances. The disturbance which folded these lake beds and locally faulted them, also folded and faulted the plateau surface, hence my statement

that "faulting and folding have affected the plateau area of central and eastern Idaho since its last elevation" but it has not destroyed its plateau character and "through all, the integrity of the old surface has persisted in a remarkable degree." From Salmon City to Gilmore, a distance of about 90 miles, the shore-line of the Miocene lake rises from 5,700 to 7,200 feet above sea, and along the same traverse the summits rise from 8,500 to 10,000 feet. Within this general rise to the southeast, however, are several subordinate anticlines and synclines.

A surface determined by the combined crestlines of the region would be "an undulating plain" dipping gently to the northwest and not a surface with maximum "declivities of but a small fraction of one degree" as Mr. Blackwelder seems to conceive it.

The casual reference which Mr. Blackwelder makes to the Payette formation as of late Eocene age, though not followed to its logical conclusion by him, touches upon what I believe to be the only essential weakness in my earlier paper. If the Payette formation is really of late Eocene age, either it must have been deposited in a different physiographic province or the old erosion surface must be crowded back, probably into the Cretaceous. I believe that the valley occupied by the Payette formation has a history coincident with the several valleys which I have studied—in fact that they are tributary to it. Near Hailey Mr. Lindgren found lacustrine deposits which, from their relations to the lavas and also from floral remains (*Sequoia angustifolia*), he believed to be Payette.[1] I have visited the Hailey locality and feel sure that the beds here mapped occupy a valley tributary to the one which earlier in this paper is described as extending from Camas Prairie nearly to Salmon City. I. C. Russel,[2] in his studies of the Snake River plains, was led to infer that the Payette formation extended eastward beneath the lavas—an inference supported by the relation of the plains to several of the old valleys which I have visited. From these observations it seems probable that the Payette formation, the lake beds at Salmon City, those at Challis, and the

[1] Waldemar Lindgren, *Twentieth Ann. Rept. U.S. Geol. Survey*, Pt. III (1898–99), p. 197.

[2] I. C. Russel, *Bull. U.S. Geol. Survey 199* (1902), p. 51.

several belts of lava in east-central Idaho all occupy valleys developed by streams of the same river system. Of these several beds, which from their topographic relations may reasonably be thought to be of about the same age, all have been referred to the Miocene except the Payette formation. In view of this fact it may be pertinent to review briefly our knowledge of the age of the Payette formation.

The Payette formation was first assigned to the Miocene,[1] but later because of a change in the reference of the deposits of Bridge Creek, Ore., which, in addition to a somewhat similar flora, have yielded vertebrate remains, it was shifted to the Eocene.[2]

The correlation of the Payette formation with the deposits of Bridge Creek is based on six species of plants which they have in common. The Payette flora, however, "embraces 32 forms, of which 17 were described as new and 5 were not specifically named, leaving, as then known [the first report] only 10 species having an outside distribution." Five of these were found at Bridge Creek "and to this list I am now able to add another species, thus making 6 of the 10 species common to these two localities."[3]

The other lake beds of the plateau region have not as yet yielded nearly as varied a flora as the Payette but it is hoped that additional search in the near future will add greatly to the collections from them. It is possible that during the next field season one of the paleobotanists of the United States Geological Survey will devote considerable time to this problem.

The only change which such studies may make in the age of the old erosion surface as now defined is to crowd it back toward or into the Cretaceous. This would result if the several localities yielded definite Eocene plant remains. The principal reason for my belief that such a change will not be made is expressed in my first paper as follows:

> It seems that the [surrounding Eocene] sediments could not have been derived from the region after its last elevation for two reasons: (1) It is very doubtful if the plateau is sufficiently dissected to afford the volume of material

[1] Waldemar Lindgren, *Twentieth Ann. Rept. U.S. Geol. Survey*, Pt. III (1900), 95.

[2] F. H. Knowlton, *Bull. U.S. Geol. Survey No. 204* (1902), p. 110.

[3] *Ibid.*, p. 110.

represented by the Eocene beds, and (2) all the more important valleys of the area drain westward, and in all probability have done so throughout their entire history. This is true of the Rocky Mountain trough, the Purcell trough, and the Snake, Salmon, and Columbia river channels. These, together with their tributaries, represent perhaps 90 per cent of the present dissection of the plateau region. If we assume that the old erosion surface is pre-Eocene the material derived from these several valleys may be thought to account for the narrow fringe of Eocene sediments on the west, but cannot account for the incomparably more extensive Eocene beds that lie to the east of the present plateau region.

In conclusion, I cannot agree with Mr. Blackwelder that "the evidence seems to show that this peneplain is much younger than Eocene and probably post-middle-Miocene." The evidence to me seems decisive that the plateau surface of the present day is much older than the late-Miocene. If it is other than Eocene, as concluded in my earlier paper, I believe that it must, because of evidence herein set forth, be crowded back toward or into the Cretaceous. Individual lines of evidence for assigning the old erosion surface of Idaho to the Eocene may not be conclusive but since all lines of approach, so far as I have been able to analyze them, point without discord[1] in the same direction, it seems to me that the assignment must be correct, and it is firmly believed that the surface does form a "valuable datum plane in broad areas where time relations between the Algonkian and the Pleistocene are otherwise obscured."

[1] Except the assignment of the Payette formation to the Eocene, as discussed above.

NOTES ON THE ORIGIN OF CERTAIN PALEOZOIC SEDIMENTS, ILLUSTRATED BY THE CAMBRIAN AND ORDOVICIAN ROCKS OF CENTER COUNTY, PENNSYLVANIA

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During the Cambrian period the North American continent subsided relative to sea-level. Before the close of the period epicontinental seas had transgressed the greater part of the continent now included within the borders of the United States, and, through the Upper Cambrian at least, limestone-forming conditions prevailed somewhat extensively in the central and southern Appalachian region. Whether this apparent subsidence was due to diastrophic movements or to the more or less complete base-leveling of Cambrian continental areas is not altogether certain. The type of sediments accumulated during Lower and Middle Ordovician time suggests that it was due to base-leveling rather than to diastrophism. In this central and southern Appalachian region great thicknesses of limestones accumulated between the Upper Cambrian and Trenton beds. Clastic sediments are sparsely represented and those which are present are peculiar in character. Yet land areas could not have been very far distant to the east and northeast, because in adjacent states this very time interval is represented by an unconformity and period of erosion, as for example in New Jersey.[1] The most reasonable explanation then seems to be that the adjacent land area had been reduced during the Cambrian to a peneplain. As a result, the streams and rivers did not have sufficient velocity to transport any considerable amount of clastic material into the adjacent epicontinental sea. Weathering processes, however, were at work and a thick mantle of residual rock waste was being prepared all over the peneplained land surface, only waiting for renewed stream activity to be

[1] Weller, *Geol. Surv. N.J., Report on Pal.*, III (1903), 15.

carried away. The soluble constituents, on the other hand, and particularly the lime carbonate, were being carried away in solution. This furnished the material for the thick calcareous deposits of early Ordovician time.

After this calcareous material was carried to the sea, the question arises as to how it was separated from solution and deposited as limestone. Marine animals could have done the work, but these deposits are strikingly unfossiliferous except at very widely separated horizons, and there are many peculiarities of the rock which cannot be explained upon this basis. Chemical precipitation has been suggested as a possible explanation, but this, too, is inadequate, as will be presently shown. The object of the present paper is to outline the probable course of events in Upper Cambrian and Lower Ordovician time which, it is thought by the author, will best explain the origin of these deposits and some of the peculiar physical characters which they now possess. The observations and deductions here recorded are largely based on field investigations carried on in the vicinity of Bellefonte and State College, Center County, Pa.

Rocks ranging in age from the Upper Cambrian through the Ordovician are exposed in an unsymmetrical eroded anticline which extends in a northeast-southwest direction across the Bellefonte quadrangle between the Bald Eagle Mountains on the northwest and Nittany Mountain on the southeast. This anticline pitches toward the northeast. Its northwestern limb is generally almost vertical and in some places even overturned by a few degrees. The southeastern limb, on the other hand, has very gentle dips, generally ranging from 8 to 15 degrees.

The lowest beds exposed are composed of limestone of variable character containing *Cryptozoon proliferum* in abundance and trilobites of Upper Cambrian age, the latter limited to thin fossiliferous layers. The fossiliferous layers are frequently oölitic and other oölitic layers occur. In addition to these, occasional layers of a peculiar conglomerate are found. This conglomerate is composed of broad, thin pebble-like structures ranging from half an inch or less up to three or four inches in diameter, and generally less than half an inch thick. The edges are rounded, the outline

circular, oval, or irregular, and the individual pebbles are either flat or rarely curved. They occur in the conglomerate closely packed together and in all positions relative to the bedding planes, flat, edgewise, or inclined. The frequency with which these broad, thin pebbles occur on edge has given rise in certain localities to the name "edgewise" conglomerate.[1]

Above these Cambrian limestones come a series of apparently unfossiliferous interbedded sandstones and limestones several hundred feet thick and very peculiar in character. The sandstones are composed of pure white quartz sand, extremely well rounded, and loosely cemented together by calcareous or dolomitic cement. Ordinary weathering conditions quickly remove this cement and the rock yields a thick mantle of sandy soil poorly adapted to agricultural purposes. On account of this character the region is locally known as the barrens. The interbedded limestones are of a peculiar character also. They are unfossiliferous in so far as they have been examined, and where they outcrop they stand up as hills above the adjacent sands.

These interbedded limestones were apparently formed under the same conditions as those of the underlying series, because they contain in places layers with the peculiar flat pebble-like structures and scattered oölite grains. Certain beds have peculiar wavy structures which give to the rock an appearance somewhat like the fossil *Cryptozoon*, but it seems to be wholly due to a mechanical distortion by lateral compression of the thin beds making up the rock. Generally the contact between these interbedded limestones and the overlying sands is very obscure because of the rapid disintegration of the sandstone. In one case the transition was observed. In it the upper layer of limestone, about a foot thick, contained numerous flat pebbles and a few oölites scattered through it. This was succeeded by about two feet of very thin-bedded fine sandstone approaching shale in appearance, with numerous sun cracks or mud cracks distinctly preserved in certain layers. Then came the sand composed of extremely well-rounded sand grains.

The next overlying formation is a limestone, sometimes sandy and sometimes shaly, carrying a rather scant fauna of Lower

[1] Stose, *Folio 170, U.S. Geol. Surv.*

Ordovician age. In addition to the sandy and shaly layers and the normal limestones, several beds of oölitic rock are also present. In these the oölites are comparatively large in size and at many horizons have been replaced by silica giving rise to the siliceous oölites of this region which are represented in almost every geological collection.[1]

Beds of the peculiar thin pebble conglomerate already described under the Cambrian also occur here and, in fact, make up a half or more of the first few hundred feet of the Beekmantown limestone. These conglomerate layers vary somewhat in character. In every case examined the pebbles consist of extremely fine-grained calcareous material and, except on weathered surfaces, the conglomerate character cannot as a rule be easily recognized. On a fractured surface the interior of the pebble-like structure is almost identical in appearance with the surrounding matrix. On a weathered surface these structures show a different, generally lighter, color and are easily recognized. They are exceedingly variable in size and shape. In some beds they are round or oval and when viewed in the hand specimen have the characteristic appearance of water-worn pebbles. They are generally thinner in one direction and in thin section often show a peculiar concentric banding following parallel to the broader sides. Occasionally a pebble can be found with a fossil shell inclosed. In the majority of the beds the pebbles are broad and flat, ranging up to three or four inches in diameter and generally less than half an inch thick. They are found in all positions in the beds, some lying flat parallel to the bedding planes and some even standing on edge. Under certain conditions these broad flat pebbles have been replaced either in part or completely by silica in the form of chert, while the surrounding matrix remains calcareous. When only partially replaced, the replacing silica forms shell-like layers around the exterior of the structure, while the central part remains calcareous and unchanged.

[1] For published descriptions of these see V. Ziegler, *Am. Jour. Sci.*, 4th ser., XXXIV (1912), 113–27; E. S. Moore, *Jour. Geol.*, XX (1912), 259–69; G. R. Wieland, *Am. Jour. Sci.*, IV (1897), 262–64; J. S. Diller, *Bull. U.S.G.S. No. 150* (1898), pp. 95–97; E. O. Hovey, *Bull. Geol. Soc. Am.*, V (1893) 627–29; E. H. Barbour and J. Torrey, *Am. Jour. Sci.*, XL (1890), 246–49.

This series of strata, ranging from the Upper Cambrian well into the Ordovician, represents a peculiar combination of oölites, rounded sand grains, and unusual conglomerate-like beds which requires more than ordinary conditions of sedimentation to explain. After detailed study both in the field and in the laboratory, it seems to the author that these structures can be best explained individually, and as a combination, by the following series of events.

Toward the close of Cambrian time an epicontinental sea covered this region. The adjacent land area was in a state of peneplanation, thus furnishing very little clastic sediment but probably still contributing considerable quantities of calcium carbonate in solution. This lime carbonate was removed from the sea water and deposited as limestone by the activities of marine organisms. Marine animals, trilobites, brachiopods, and probably many other less highly organized types like the sponges aided in this work, but the greater part of the separation and secretion of the lime was brought about by marine algae which gave rise to the oölites and peculiar pebble-like structures. Then the region was somewhat elevated and sand-dune conditions prevailed. These marine limestones were covered over by a thick blanket of wind-blown sand. This material was worked over by the wind so long and so thoroughly that even the minute grains were rounded into almost perfect spheres. This sand resembles, but is even more rounded than, the beach and dune sand along the Florida coast today, which has gradually been carried southward by the wind and water and rounded during its journey. The region was not very far above sea-level and at least twice during the accumulation of these sands it was submerged and thin beds of limestone similar to those of the preceding period were formed. After this complete series of sandstones and limestones had accumulated, the whole region was finally submerged and the continuous marine sedimentation of early Beekmantown time was inaugurated. However, marine algae were still the important agents in producing the limestone, because, as already noted, oölitic limestone and siliceous oölite occur at numerous horizons and a large percentage of the lower beds is composed of the peculiar pebble-like conglomerate secreted by the algae.

These structures are of sufficient importance to require further explanation and it will be advisable to consider them one at a time, taking the conglomerates first, the oölites next, and the interbedded sands last.

ORIGIN OF THE CONGLOMERATE-LIKE STRUCTURES

Conglomerates from widely separated regions, similar to those here mentioned, have previously been described by other authors.

In 1906 a similar if not identical conglomerate was described by Seeley from Division D of the Beekmantown of the Champlain Valley, under the name of the Wing conglomerate.[1] He quotes Wing's original description of this conglomerate as follows: "A conglomerate made from flat and rounded pebbles from the quartzite below, the flat ones one or two inches across, the rounded ones from coarse shot to large bullets, the paste a limestone." After questioning as to the origin of these pebbles, Seeley remarks that the associated deposits seem to have been laid down in quiet waters and that the flattened pebbles, as described by Wing, stand on edge and at all angles. He was unable to imagine how in either swift or slow water these pebbles could be laid down as they are if they were of clastic origin. As a result of his studies he concluded that they were organic and he described the pebbles as *Wingia*, a new genus of Beekmantown sponges.

In 1909 Stose described conglomerates identical with those now under discussion from the same geological horizons near the southern boundary of Pennsylvania.[2] He offers the following explanation of their origin:

> At the beginning of the Conococheague an uplift occurred that raised a part of the sea bottom into land. The freshly deposited sediment was broken up and its fragments formed conglomerates, which also contain numerous rounded quartz grains. Other thin layers of limestone were broken up by the waves into "shingle" or flat fragments that were shuffled about on the beaches and formed "edgewise" conglomerates.

A very careful study of these conglomerates, both in the laboratory and in the field, with attention directed not only to the larger

[1] H. M. Seely, *Report of the Vt. State Geol.* (1906), pp. 174–78.

[2] G. W. Stose, *op. cit.*

structures of the conglomerate bed, but also to the minute microscopic structure of the individual pebbles, has brought out some interesting features not hitherto noted in the descriptions. It has already been stated that these peculiar conglomerate pebbles have a wide range in size and shape and that they occur associated with oölite grains. Although the pebbles are broad and flat, the edges and corners are always rounded. Thin sections cut from these pebbles show a peculiar banding in the broad flat types and a concentric structure in the smaller rounded specimens (Figs. 1, 2). The pebbles are frequently partially or completely replaced by silica in the form of chert. In such cases the matrix weathers away and leaves the replaced pebbles like chert concretions. If the replacement is incomplete and a joint plane passes through the pebble, the central unreplaced part also weathers out, leaving the chert nodule hollow.

FIG. 1.—Cross-section of a broad flat pebble as it appears on a weathered surface. The weathering brings out the arrangement of the laminae. Natural size.

As an outcome of these studies it has been concluded that these structures are organic, resulting from the activities of calcareous algae. This conclusion differs from Seeley's in assigning the origin to algae instead of sponges. Seeley was undoubtedly led to assign these structures to the sponges because of the frequency with which he found them containing silica. He describes *Wingia* as "a calcareous fossil sponge, with or without siliceous spicules . . . . the essential structure a collection of pillae or tufted balls, these mostly 0.25 mm. in diameter, massed without definite arrangement or rarely more loosely distributed through the containing calcite." These siliceous structures are no doubt replacements of the original calcite similar to those found both in the pebbles and in the oölites of the Pennsylvania region.

The importance of the lime-secreting algae seems to have been generally overlooked in explaining the origin of early Paleozoic limestones. Even in the building-up of modern calcareous deposits

these forms have been given scant credit. A recent contribution on this subject[1] by Howe has indicated how important these organisms really are in building up the reefs of today. The lack of recognition of these forms as important reef-builders is no doubt due to two facts. In the first place, the skeletons of these calcareous algae either have been assigned to true corals and therefore credited to the animal kingdom, or, on the other hand, they have perhaps been considered by some, direct chemical precipitates rather than organic structures. In the second place, these calcareous algal skeletons lose their organic character with great rapidity. Walther has shown by his studies on the *Lithothamnion* bank in the Bay of Naples that by the action of the percolating water the *Lithothamnion* structure is gradually obliterated and the calcareous mass becomes a structureless limestone. In studying Nullipore chalk from the Tertiary and from the Lias, Walther found that in many parts there occurred well-preserved specimens but in other parts a gradual obliteration is observed of all plant structures until the rock becomes entirely structureless. If this be true for a form like *Lithothamnion* which is known to secrete a calcareous skeleton whose mineral composition is calcite, it is not surprising that all trace of organic structure is lost in other types which, like *Halimeda*, secrete their skeleton in the mineral form of aragonite.[2]

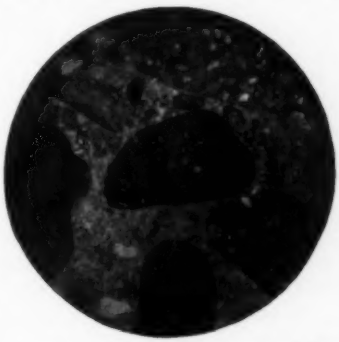

FIG. 2.—Thin section of small pebbles showing concentric structure. Enlarged.

It is freely admitted that in these pebble-like structures from the Cambrian and Ordovician limestones no organic structure has been found sufficiently well preserved to prove conclusively that they are of algal origin, but their similarity to such structures now forming is very suggestive. In this connection it is worth

[1] M. A. Howe, "The Building of 'Coral' Reefs," *Science*, May 31, 1912.

[2] W. Meigan, *Centralblatt für Min., Geol., und Pal.* (1901), pp. 577, 578.

while to compare the following quotations concerning modern occurrences.

There is also a small vegetable group, that furnishes a considerable quota toward the composition of the characteristic coral-rock. It is that of the peculiar seaweeds or lower algae known as Corallines or Nullipores. They are distinguished by the incrustment of their tissues with carbonate of lime, to such density that their vegetable nature is completely disguised; and, excepting for the absence of the characteristic pores, they might in many instances be mistaken for the coralla of the hydroid coral Millepora. . . . . In the deeper rock pools, and on the sea bottom generally, in the neighborhood of the reefs, another generic form, Halimeda, belonging to the same nullipore tribe, is locally abundant. This type forms erect, branching tufts, often several inches in length, of which the branchlets are composed of flattened, irregularly polygonal, or more or less fan-shaped, calcareous disks, strung together, as it were, in a moniliform or chainlike order. While growing, this nullipore is a brilliant grass-green, but it bleaches, when dead, to a pure white. The bleached discoidal segments of its disintegrated fronds often occur in great abundance among the mixed calcareous components of reef-rocks and coral sand.[1]

In describing the reefs of the Bahamas Agassiz says:

Nullipores are most abundant on the summit of the reef, growing upon the smaller fragments of broken corals, which they also often cement together, when they are forced inward into the deeper part of the lagoon, where the cemented masses frequently form heads of considerable size. Longitudinal and cross-sections of the lagoon show that its bottom is uniformly covered with coarse sand and broken shell material, or fine sand, according to the distance from the action of the breakers. Upon this looser material algae and corallines thrive and grow abundantly, generally in large patches.[2]

Immense masses of nullipores and corallines grow on the shallowest flats, on the tops of the branches of madrepores which have died from exposure to the air, either because they have grown up to the surface and so have become exposed by extreme low tides, or because strong winds have blown the water from the flats.[3]

Not only are the Nullipores very abundant in many of the modern coral reefs but they also seem to be able to grow with great rapidity and they can live under all conditions—in deep water beyond the range of corals; in shallow water where they are

[1] W. Saville Kent, *The Great Barrier Reef of Australia*, (1893), pp. 140–41.

[2] Agassiz, *Bahamas*, p. 104; *Bull. Mus. Comp. Zoöl.*, XXIV (1894).

[3] Agassiz, *Three Cruises of the "Blake,"* I, 82.

uncovered for a part of the time each day; in the tropics where the water is warm; and in the cold waters north of the polar circles.

The remarks of Saville Kent concerning the disklike fragments of *Halimeda* mingled with the sands of the great barrier reef are very suggestive of the disklike structures here described. The range in size of these disks is very much greater than that found in the modern *Halimeda* but it is quite possible that a giant *Halimeda*-like form existed in these early paleozoic seas and gave rise to the structures here described.

One feature of the conglomerate beds yet awaits explanation; namely, the peculiar position frequently occupied by the broad flat pebbles, either on edge or at any angle to the bedding planes. Several explanations of this feature have previously been offered. As noted above, Seeley believed these pebbles were formed by sponges growing in place. Stose thought that they were formed by thin limestone layers breaking into small flat plates or shingle and tossed about on a tide-swept flat. When the tide came in, these flat fragments were washed together in all positions and held by a soft paste which surrounded them. This explanation seemed impossible to the author for two reasons: first, it would not account for the wide variations in the thickness of the conglomerate beds, which varies from a few inches to several feet, each bed being a definite unit and separated from those adjacent by parallel bedding planes; and secondly, it seemed impossible to conceive of the physical conditions which could roll these flat pebbles around until their edges and corners were rounded and then leave them indiscriminately mixed with a soft matrix, some lying flat, some on edge, and others at all possible angles between these two.

The true explanation of the origin of these conglomerates became apparent when a locality was visited along the railroad cut of the Lewisburg and Tyrone division, Pennsylvania R. R., beside the Logan Branch of Spring Creek, at a point opposite the Nittany Furnace in Bellefonte. At this point several hundred feet of limestone beds are exposed in a steeply dipping series along the railroad cut. The excavation in this cut has exposed the beds in vertical section and the arrangement of the broad flat pebbles becomes at once apparent. This arrangement is clearly shown in

the accompanying diagram and photograph (Figs. 3, 4). Here the pebbles are seen to be arranged in unsymmetrical wavelike or ripple-like structures which traverse the limestone. In this cut the beds are exposed at right angles to these wavelike structures and the arrangement is brought out with almost diagrammatic clearness. Each series of waves is confined to its own particular stratum of the limestone. When the wavelike layer of flattened pebbles arches up to form an unsymmetrical anticline the fine-

FIG. 3.—Photograph of a thin conglomerate layer in place, near Bellefonte, Pa.

grained material fills the space beneath the anticline down to the prominent bedding plane below. The space between the upper surface of this pebble layer and the next overlying prominent bedding plane is also filled by fine-grained material, which thickens over the synclines and thins out over the anticlines.

The explanation offered for these structures is this: The sediments composed of fine-grained calcareous mud resulting from the grinding-up of calcareous organic structures by wave action and broad flat pebble-like bodies which were the skeletons of cal-

careous algae accumulated on the gently sloping bottom of the sea. When in their original position these pebbles were all flat and parallel to the bottom; in other words they lay parallel to the bedding planes. At periodic intervals these beds of calcareous mud and intermingled pebbles slumped or slid along the bottom under the influence of gravity. At the time of the slump or slide the matrix around the pebbles consisted of incoherent lime mud or paste. As it moved it developed unsymmetrical waves or ripples

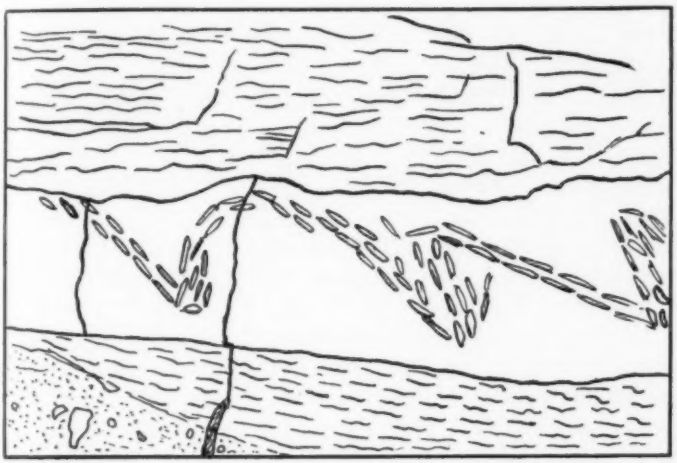

FIG. 4.—Diagram illustrating the arrangement of the pebbles shown in Fig. 3. The conglomerate bed is 6 inches thick and the distance from crest to crest of the wavelike structures is 9½ inches.

in its mass, just as a thin sheet of water develops ripples as it flows down a smooth, gently sloping surface. The whole layer of sediment when it finally came to rest—and the whole distance moved may have been only a few inches or possibly a few feet—settled into a uniform layer once more, but the inclosed pebble-like structures had been moved from their original horizontal position, and occurred at all angles with the original bedding planes. In these new positions, surrounded by the matrix of lime mud, they were in perfect equilibrium and there they remained until the lime mud became transformed into limestone. And there we find them today when

properly exposed in cross-section, still indicating the wavelike flowing motion which brought them into their present position.[1]

ORIGIN OF THE OÖLITES

Oölites are widely distributed in the rocks of this country and Europe and are found at many horizons from the Cambrian (or even pre-Cambrian)[2] to the present. They are known to be accumulating today at numerous places among which may be mentioned certain coral reefs in the open sea, as, for example, those around Bermuda and the Bahamas, in Salt Lake, Utah, and in certain petrifying springs like those at Carlsbad.

The oölites of the central Pennsylvania region are somewhat variable according to the horizon at which they occur. In the Upper Cambrian limestones they are apparently all calcareous, either spherical or oval in shape, composed of concentric layers of material generally showing a radial fibrous structure. Between crossed nicols some of the spherules show a characteristic dark cross, while others have been almost completely transformed into a single calcite crystal with twin lamellae distinctly developed. No nuclei of foreign material were observed; the fibrous concentric structure continued to the center, or the calcite crystal occupied this central position with only the marginal fibrous part remaining. Associated with these spherical forms were numerous oval and rodlike structures having an internal make-up similar to that of the oölites. The spherical oölites range in diameter from 0.28 mm. to 0.73 mm. The oval and rodlike grains also show considerable variation in size, as these measurements will show: large oval oölite grain, long diameter 1.02 mm., short diameter 0.57 mm.; small oval grain, long diameter 0.86 mm., short diameter 0.28 mm.; long rodlike grain, long diameter 2.04 mm., short diameter 0.28 mm.

The siliceous oölites and the associated calcareous oölites from the Ordovician beds are sometimes larger in size. Several measure-

[1] I am indebted to Professor A. W. Grabau and Dr. F. F. Hahn of Columbia University, who first brought this explanation to my attention. Dr. Hahn has made a special study of such motion in stratified deposits. He informs me that in recent sediments in the Zuider Zee such a slumping or flowing of the sediments has been observed where the slope of the bottom did not exceed four degrees.

[2] See Geikie, *Text-Book of Geology*, p. 192, footnote.

ments of the spherical grains from that locality where they seem to be largest show that the range for the diameters is between 1.00 mm. and 1.33 mm. Many of the grains are partially or completely replaced by silica and a rounded sand grain frequently forms the nucleus around which these oölites have formed. In the course of this replacement the central nuclear sand grain is sometimes secondarily enlarged, showing a zonal structure in optical

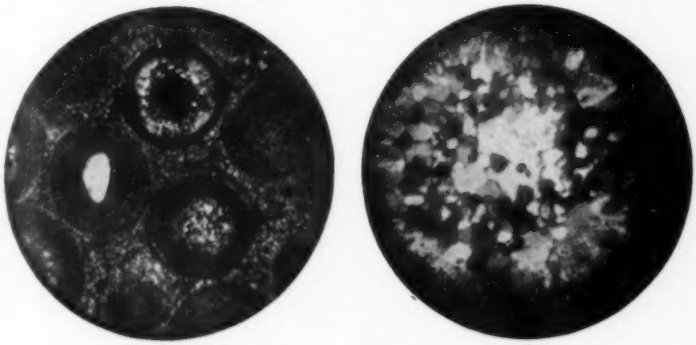

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FIG. 5.—Photomicrograph of siliceous oölite; ×22. The oölite on the left shows an oval sand grain as a nucleus, surrounded by cryptocrystalline quartz, with a narrow zone of minute quartz crystals radially arranged around the outer margin. The upper oölite shows the central nuclear quartz grain secondarily enlarged into a quartz crystal with part of the crystal faces developed. The lower oölite shows the central space occupied by an aggregate of minute quartz crystals. Nicols crossed.

FIG. 6.—The interior of the oölite of Fig. 5, ×130, showing the crystal outlines of the minute quartz grains which compose it. Nicols crossed.

continuity with the original grain and sometimes with more or less completely developed crystal faces. The outer zones of the spherules are generally replaced by cryptocrystalline quartz or chert. When no nucleus is present this chert may extend to the center or the center may be occupied by numerous distinctly crystallized quartz grains. Some of these show crystal faces as if the minute central cavity had been filled like a tiny geode. Another very interesting feature is the secondary enlargement of the spherules by one or more zones of crystalline quartz deposited in minute radial crystals arranged in zones around the original granule, with the long axes of the crystals arranged normal to the outer surface of the sphere (Figs. 5, 6).

Two theories have been advanced to explain the origin of these oölitic grains. Some hold that they are chemical precipitates and that the concentric oölitic structure is produced by successive layers of calcareous or siliceous deposit laid down on minute fragments of shells, sand grains, etc., in highly calcareous or siliceous waters. An alternative hypothesis, and one which seems more probable, is that cellular plants (algae) have extracted lime carbonate from the water, and have built this up into oölite grains with a concentric and fibrous radiated structure. All other types of oölites are then derived from these original calcareous grains by replacement. Such lowly organized plants can live even in hot waters, and oölite grains are now forming in springs like those at Carlsbad, due to the activity of algae.[1] In 1891 Rothpletz visited Salt Lake and made a detailed study of the oölitic sand now forming along the shore.[2] He found that oölites dredged up from the bottom, which had not been worked over by the waves, were covered with a deep bluish-green mass of algae among which he recognized *Gloeocapsa* and *Gloeotheca*. As a result of his studies he concludes:

> The oölites of the Great Salt Lake are, therefore, indubitably the product of lime-secreting fission-algae, and their formation is proceeding day by day. . . . . According to the present stage of my researches, I am inclined to believe that at least the majority of the marine calcareous oölites with regular zonal and radial structure are of plant origin, the product of microscopically small algae of very low rank, capable of secreting lime.

Another interesting suggestion, particularly when considered in connection with the foregoing discussion of the algal origin of the conglomerate-like beds, is that made by Seeley in which he called attention to the close resemblance of the internodal grains of Nullipores to grains of oölite as furnishing a further explanation of oölitic texture. These grains show a concentric structure as well as a radiated tubular structure, which would favor the recrystallization such as commonly occurs.[3]

In 1903 G. Linck published the results of his investigations

[1] Geikie, *Text-Book of Geology*, I, 191.

[2] *Botanisches Centralblatt*, Nr. 35 (1892). Translated in *Am. Geol.*, X (1892), 279–82.

[3] H. G. Seeley, *Brit. Assoc. Adv. Sci., Bath* (1888), *Proc.*, pp. 674–75.

concerning the origin of oölites.[1] He proved that in every recent occurrence of oölite of which he was able to obtain samples, the oölite grains consist of the mineral aragonite, while in the older or fossil types they consist of calcite. He concludes that all oölites were originally formed as aragonite and later changed to the more stable mineral form calcite. But aragonite cannot form under any ordinary marine- or fresh-water conditions due to simple concentration of the solution of calcium bicarbonate. There are then two possible conditions under which the aragonite oölites might have accumulated. They might be the products of organic activity, for it is known that both animals and plants have the power to abstract calcium carbonate from the water and build it up into their skeletons in the form of aragonite. The skeletons of many of the coralline algae, for example, are formed in this way. The oölite grains might also be produced by direct chemical precipitation due to some special precipitating agent. By experimental research Linck found that, under ordinary conditions of temperature, the calcium carbonate would be precipitated from the calcium sulphate of sea water by the addition of sodium carbonate or ammonium carbonate. When so precipitated it assumed the mineral form aragonite. As a result of his investigations he concluded that although the solution of calcium carbonate (bicarbonate) in sea water was always below the saturation point, and therefore direct precipitation due to concentration could not take place, yet sodium carbonate or ammonium carbonate might arise, due to the decay of plant or animal tissues, and that these reagents would precipitate the calcium carbonate from the ordinary sea water, under either cold or warm climates, in the form of aragonite, and that in this way the oölite grains were formed.

This theory does not eliminate the organic factor in the production of oölite grains, but makes the organisms indirect agents which produce by their decay sodium or ammonium carbonate, the precipitating reagents, instead of directly building the oölite grains by their organic activity.

It would therefore seem that under either the organic or inorganic theory of origin we must postulate the presence of organisms

[1] *Neues Jahrbuch für Min., Geol., und Pal.*, Beilage-Band XVI (1903), 495–513.

to cause the formation of oölites. Now, since many of the oölite layers show no evidence of the presence of animal fossils, it would seem to be reasonable to assume that the organic agents were marine algae, either of the coralline type, somewhat similar to those which abound wherever oölites are known to be forming in the open sea today, or minute algae similar to those which are known to be active in the formation of oölites in Salt Lake or the hot springs of Carlsbad.[1]

In spite of recent publications to the contrary,[2] the author has in his possession material which will, he is convinced, when thoroughly worked up, prove that every occurrence of siliceous oölite in the Ordovician rocks of Pennsylvania is due to the direct replacement of an original calcareous oölite by silica. These siliceous oölites occur at many horizons and in many localities. They sometimes occupy widely extended layers, and sometimes occur as nodules in layers where the surrounding oölites are either calcareous or changed to dolomite. In every case when found in place, their field association and microscopic character is such that they could not have formed as direct chemical precipitates.

ORIGIN OF THE BARRENS SANDSTONE

As already noted, these sandstones are composed of fine, extremely well-rounded sand grains cemented by a calcareous or dolomitic cement which easily weathers out and gives rise to a thick mantle of residual sand. The sand grains seem to be uniformly rounded regardless of size. A thin section cut from the basal member of this series showed grains ranging from 0.17 mm. to 0.73 mm. in diameter (see Fig. 7). A sample of the residual sand from the middle of the series gave measurements from 0.13 mm. to 0.71 mm., and a similar sample from the upper beds showed diameters from 0.26 mm. to 0.86 mm.

As is well known, such fine sands could not have been rounded to such a degree in water. It seems, therefore, that the origin of these sands and sandstones must be assigned to the work of the

[1] The author has under way a further investigation of the origin of oölites, but the results are not yet available for publication.

[2] Ziegler, *Am. Jour. Sci.*, 4th ser., XXXIV (1912), 113–27.

wind. These sands are almost always pure white in color, differing from typical desert sands, which are generally some shade of red or brown, so that in all probability desert conditions did not prevail here. It was more likely a stretch of sand-dune country that lay along the low, flat Upper Cambrian shore. At that early day those types of plant life which check the development of sand dunes along our shores today did not exist and perhaps there was no other type of plant to take their place. As a result the wind had unhindered opportunity to get at and work over this sand. The climate need not have been very dry, because, as Shaler has shown, rain does not have an important retarding effect upon wind-blown sand.[1] Even heavy and long-continued rains falling upon dune sand rarely wet it for more than an inch below the surface. In a few hours after the rain is over, this thin film of water is evaporated from the surface and the wind is free again to move about the sand. The cross-bedding shown in the few localities where this sandstone outcrops is altogether consistent with this sand-dune theory of origin. When again the region became submerged, a little of the finer sand was carried out and dropped in the water. These grains then frequently served as the minute nuclei around which calcareous oölites formed, which were in many cases later replaced by silica and gave rise to the extensively developed siliceous oölites of the overlying beds.

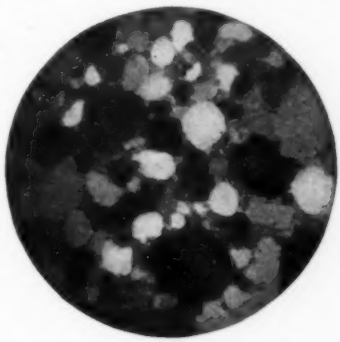

FIG. 7.—Photomicrograph of the Barrens sandstone. ×22. Nicols crossed.

This sand-dune theory of the origin of the sandstone beds does not require great changes in the conditions of sedimentation from the Upper Cambrian to the Lower Ordovician of this region, nor does it require long periods of time to produce the well-rounded character of the sand. Mackie has shown that sand carried by the wind for a very few miles will be more thoroughly rounded than

[1] N. S. Shaler, *Bull. Geol. Soc. Am.*, V, 207–12.

similar sands carried for many miles by water or subjected to long-continued churning by the waves.[1]

A slight elevation of the region, perhaps only a few score feet, would allow the sand dunes to migrate out over the Upper Cambrian limestones. No elevation of the adjacent land area is necessary to account for the transportation of the sand, because the wind is well able to transport sand grains of such small size for long distances if not interfered with by vegetation. Very slight depressions would account for the thin interbedded limestones, and a general though gentle submergence of the whole area would inaugurate Beekmantown time.

[1] Mackie, "On the Laws That Govern the Rounding of Particles of Sand," *Trans. Edinburgh Geol. Soc.*, VII, 298–311; see also pp. 148–72 (1897).

THE SECONDARY PRECIPITATION OF GOLD IN ORE BODIES

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Secondary enrichment of ore deposits has been recognized as a subject of fundamental importance to the economic geologist, and in recent years has received considerable study, both in the field and in the laboratory. The chemical reactions involved are, in many cases, less complex and more readily susceptible to laboratory study than many of the other great problems of earth chemistry. The temperatures, pressures, and concentrations involved are well within the range easily obtainable in the laboratory; the reacting substances are less numerous, and their chemistry is better understood than is the case with the substances and reactions involved in petrogenesis.

In December, 1909, Emmons[1] published a paper calling attention to the relationship between placer deposits and manganiferous and manganese-free gold ores, suggesting manganese as a determining factor in the solution of gold. About the same time the writer began a series of experiments dealing with the solution of gold in secondary enrichment, the results of which were published in May 1910.[2] In October, 1910, Emmons published a somewhat comprehensive review of the chemical and geological data available, with special reference to the gold deposits of the United States.[3] Very little material bearing on the subject has appeared since that time, and at the suggestion of Dr. Emmons the writer undertook a series of experiments with the hope of clearing up some important points in connection with the chemistry of the precipitation of gold, and in particular, of establishing the peculiar set of conditions under which gold and manganese dioxide may be precipitated

[1] W. H. Emmons, *Min. and Sci. Press*, XCIX, 751–54, and 782–87 (1909).

[2] A. D. Brokaw, *Jour. Geol.*, XVIII, 321–26 (1910).

[3] W. H. Emmons, *Trans. Am. Inst. Min. Eng.*, XLII, 1–73 (1911).

simultaneously, since manganese dioxide has been considered favorable, if not essential, to the solution of gold in secondary enrichment.

The methods of precipitation here discussed are not necessarily limited to secondary enrichment. Gold from a primary deposit may be recrystallized; that is, may be dissolved and reprecipitated without appreciable transportation, and in this case no enrichment would be accomplished, though the chemistry of the precipitation might be essentially the same as that in which gold deposits are enriched. For this reason the writer does not hesitate to draw examples from deposits where the gold has been recrystallized by secondary processes even though the deposit is not thought to have undergone any appreciable enrichment.

The substances in an ore body, capable of precipitating gold from a solution in which it is held as a chloride, may be grouped as follows:

I. Native elements, copper, silver, mercury, tellurium.
II. Sulphides, tellurides, etc.
  a) Simple—most of the common sulphides.
  b) Complex—sulph-arsenides and antimonides.
III. Ferrous compounds.
  a) In solution derived from alteration of iron sulphides.
  b) Primary minerals, as siderite, iron bearing calcite, etc.
IV. Manganous compounds.
  a) In solution, derived from alteration of manganese minerals.
  b) Primary, rhodochrosite.
V. Other inorganic substances, sulphur dioxide.
VI. Organic compounds.

I. NATIVE ELEMENTS

The metals preceding gold in the table of electrolytic solution tension[1] are capable of displacing it from solutions of its salts. The reaction may be expressed ionically as follows:

$$Au^{+++} + 3Me = Au + 3Me^{+}$$

in which Me stands for one equivalent weight of the metal in question. Copper and silver are not uncommon in gold deposits and are capable of bringing about such precipitation. Doubtless

[1] See Smith, *General Inorganic Chemistry*, p. 670; Walker, *Introduction to Physical Chemistry*, or any textbook of physical chemistry.

native mercury, arsenic, and antimony can act in a similar way. There is, however, little geological evidence of such precipitation, though it is conceivable that electrum may sometimes be formed in this way. Ransome[1] mentions the association of wire gold with native silver in the Breckenridge district, and here the silver may have been the precipitating agent. The other metals having a higher electrolytic solution tension than gold and occurring free in nature are not common in gold deposits, and no record of their having caused precipitation of gold is found. Tellurium, usually classed as a non-metal, may interact with gold chloride in solution to precipitate gold, as shown by the following equation:[2]

$$3Te+4AuCl_3=4Au+3TeCl_4$$

This may account, in part, for the precipitation of gold in the oxidized portion of gold telluride deposits.

II. SULPHIDES, TELLURIDES, ETC.

a) *Simple sulphides.*—That sulphides are capable of precipitating gold has been known for many years. In 1866 Wilkinson[3] showed that metallic gold is precipitated by the sulphides of copper, iron, arsenic, lead, zinc, molybdenum and tungsten, and to this list Skey[4] added the sulphides of tin, bismuth, platinum and gold. These investigators showed that the precipitates obtained were metallic gold, not gold sulphide, though the latter would be the compound naturally expected by some such reaction as follows:

$$2AuCl_3+3ZnS=Au_2S_3+3ZnCl_2$$

It is of interest to consider the possible reasons for the precipitation of the metal instead of the sulphide.

Hydrogen sulphide, under ordinary conditions of temperature and pressure in the laboratory, reacts with gold salts in solution to form Au_2S_2,[5] a stable sulphide of extremely low solubility, as follows:

$$8AuCl_3+9H_2S+4H_2O=4Au_2S_2+24HCl+H_2SO_4$$

[1] F. L. Ransome, *U.S. Geol. Survey, Professional Paper No. 75*, p. 82.

[2] V. Lenher, *Jour. Am. Chem. Soc.*, XXIV, 355 (1902).

[3] *Trans. Roy. Soc., N.S.W.*, VIII, 11 (1866).

[4] *Chem. News*, XXIII, 232; see *J. B. u. d. Fortschritte d. Ch.*, 1871, p. 344.

[5] Gmelin-Kraut, V, P. II, p. 268.

Hydrogen sulphide may be formed by the interaction of acid mine waters on mineral sulphides, for example, on zinc blende, as follows:

$$H_2SO_4+ZnS=H_2S+ZnSO_4$$

This reagent is doubtless an important precipitant for gold in such waters. Why then, does it throw down metallic gold in nature, instead of gold sulphide, as in the laboratory?

A number of factors may be mentioned as probable causes. Hydrogen sulphide is given off very slowly by most of the mineral sulphides except pyrrhotite and zinc blende, even in fairly strongly acid solutions. It has been shown that in the presence of auric chloride, gold sulphide is oxidized to metallic gold and sulphuric acid, with the further precipitation of gold from the solution,[1] probably according to the equation:

$$Au_2S_3+4AuCl_3+8H_2O=6Au+2H_2SO_4+12HCl$$

Since the hydrogen sulphide is very slowly evolved, it may be that the gold sulphide is momentarily formed and immediately oxidized by the adjacent gold chloride molecules, which have not yet been attacked by the hydrogen sulphide. The reaction was tested experimentally by placing in a dilute solution of gold chloride fragments of pyrrhotite and zinc blende, the mineral sulphides which give off hydrogen sulphide the most readily and are therefore the most favorable for the precipitation of gold sulphide. In the case of zinc blende the surface of the crystal was covered with shining flakes of gold after standing 24 days. No gold sulphide could be distinguished. In the case of pyrrhotite the action was more rapid and the gold was completely precipitated in 3 days, but here again no gold sulphide was detected. The pyrrhotite was covered with a dull yellowish-brown coat, which, under the microscope was shown to be made up of minute crystals of gold, partly imbedded in material resembling limonite.

A second possibility is that ferric salts may oxidize the gold sulphide in a similar fashion. With this in mind, a solution of gold chloride and ferric sulphate was treated with hydrogen sulphide solution until a dark precipitate began to form. A small amount

[1] Gmelin-Kraut, *loc. cit.*

of sulphuric acid was added to suppress the precipitation of ferrous sulphide. The solution and precipitate were allowed to stand over night, then filtered, and the precipitate was taken into solution with fuming nitric acid and a small amount of concentrated hydrochloric acid. If any sulphide were present it would be oxidized to sulphate under these conditions. The solution was diluted and filtered; barium chloride solution gave no precipitate, showing the absence of sulphates, and thus proving that no gold sulphide was present in the precipitate. It is conceivable under these conditions that the hydrogen sulphide may have reduced some of the ferric salt before the gold began to precipitate and that the ferrous salt precipitated the gold. If this had been the case the precipitate should have shown the presence of sulphur, according to the reaction:

$$Fe_2(SO_4)_3+H_2S=2FeSO_4+H_2SO_4+S$$

which takes place before the precipitation of ferrous sulphide begins. The action of the nitric acid in the above experiment would have oxidized such precipitated sulphur to sulphuric acid, and as the test showed the absence of sulphates it is evident that the above reaction did not take place, but that the hydrogen sulphide acted on the gold chloride. The gold sulphide, Au_2S_2, was probably formed first, then quickly oxidized to metallic gold and sulphuric acid by the ferric sulphate present.

A further experiment along the same line was made as follows: Gold sulphide was precipitated and placed in contact with ferric sulphate, free from ferrous salt. After two weeks the solution contained a noticeable amount of ferrous salt, showing that part of the ferric salt had been reduced by the gold sulphide, but the appearance of the precipitate had not changed appreciably. Fresh ferric salt solution was added with similar results, and after standing three months small particles of what appeared to be gold could be seen. They could not be separated from the gold sulphide however, and the evidence that they were particles of gold is far from conclusive.

From these experiments it seems likely that the presence of ferric salts tends to cause the precipitation of free gold rather than

gold sulphide, in the presence of hydrogen sulphide and sulphuric acid. Equations may be written as follows:

$$8AuCl_3+9H_2S+4H_2O=4Au_2S_2+24HCl+H_2SO_4$$

$$Au_2S_2+6Fe_2(SO_4)_3+8H_2O=2Au+12FeSO_4+8H_2SO_4$$

These reactions may help explain the fact that, so far as we know, gold sulphide does not occur in nature.

A number of natural tellurides, including all the commoner telluride ores, have been shown to react with gold chloride in a manner similar to that of free tellurium,[1] for example:

$$3Au_2Te+4AuCl_3=10Au+3TeCl_4$$

and as is the case with tellurium, this may help to account for the free gold in the oxidized portion of the ore body, such as the "rusty gold" or "flour gold" at Cripple Creek.

b) *Complex sulphides.*—From the fact that most of the simple sulphides precipitate gold from solution it is readily inferred that complex sulphides would be equally effective as precipitants. Polybasite was chosen for an experiment on this point. A small fragment of a good crystal of polybasite (Ag_9SbS_6) was placed in 5 c.c. of gold chloride solution containing 0.5 per cent gold. After 10 days the gold had been completely precipitated, forming a dull coat over the crystal, resembling that formed on pyrrhotite. Doubtless many of the complex sulphides would react in a similar manner, though geological observations bearing on such precipitations are lacking. Perhaps this is because the complex sulphide, after precipitating gold, has been more or less completely removed by oxidation.

III. FERROUS COMPOUNDS

a) *In solution.*—The fact that ferrous salts can precipitate gold from solutions of its salts has long been known. The reaction is ordinarily written:

$$3FeSO_4+AuCl_3=Au+Fe_2(SO_4)_3+FeCl_3,$$

or ionically,

$$3Fe^{++}+Au^{+++}=3Fe^{+++}+Au$$

This reaction was formerly used in metallurgical practice, but recently has been largely displaced by other methods. The

[1] V. Lenher, *op. cit.*

most abundant source of ferrous sulphate in mine waters is found in the iron sulphides, which, upon partial oxidation, give rise to ferrous sulphate and sulphuric acid. These are almost always present in the zone where the sulphides are undergoing oxidation, and, because of the downward movement of the waters, and the presence of reducing agents lower down, ferrous salts are likely to be abundant below this zone. In such an ore body gold cannot migrate far, since ferrous salts, even in small amounts, almost prohibit the transportation of gold in solution.[1] Ferrous salts in solution are more abundant in mine waters than is hydrogen sulphide, and are doubtless a more important factor in the secondary precipitation of gold.

McCaughey[2] showed the effect of ferrous salts on the solubility of gold in concentrated solutions of ferric salts, and doubtless an equilibrium condition exists between the concentrations of ferrous, ferric, and gold salts in solution, in contact with metallic gold. The equation may be written in the ionic form:

$$3Fe^{+++}+Au=3Fe^{++}+Au^{+++}$$

whence the equilibrium equation:

$$\frac{[Fe^{++}]^3\times[Au^{+++}]}{[Fe^{+++}]^3}=K$$

McCaughey's results were not sufficient to give the value of this constant, but more complete experiments would doubtless show such a relationship—indeed the form of curve obtained shows qualitatively that some such relationship exists.

If the condition of equilibrium were satisfied, fluorite may disturb it by going into solution and giving rise to the fluoride ion, which forms a little dissociated complex with the ferric ion,[3] practically removing it from the system and allowing the ferrous ion to cause precipitation. This case, though theoretically possible, is probably not of great importance in nature on account of the very low solubility of gold in ferric salts at concentrations obtaining in mine waters.

[1] McCaughey, *Jour. Am. Chem. Soc.*, XXXI, 1261 (1909). See also Emmons, *loc. cit.*

[2] *Loc. cit.*

[3] Stieglitz, *Qualitative Analysis*, Part I, 271 (New York, 1912).

b) *Primary iron minerals other than sulphides.*—Siderite is capable of precipitating gold from solution as follows:

$$AuCl_3+3FeCO_3+3H_2O=Au+3CO_2+FeCl_3+2Fe(OH)_3$$

Of this reaction we have geological evidence in the form of gold pseudomorphs after siderite, in which gold gives a sort of skeleton of the siderite replaced, since its volume is less than that of the siderite.

The specimen shown in Figs. 1, 2, and 3 is from the collection in Walker Museum, University of Chicago. The precipitation of gold by means of siderite was easily accomplished in the laboratory. A

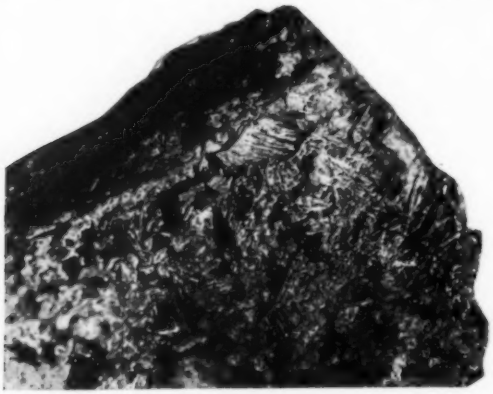

FIG. 1.—Gold replacing iron carbonate. × 2

cleavage block of light-colored siderite was placed in 10 c.c. of 0.5 per cent gold solution, and after two weeks flakes of gold could be distinguished on the faces of the mineral. In another experiment sulphuric acid was added to the gold chloride solution. In this case the precipitation was more rapid, the siderite being nearly covered with shining flakes of gold after four days. After two weeks typical "wire gold" was noted, more or less coated with limonite. It is worthy of note that many occurrences of wire gold are found imbedded in a gangue of limonite. Ransome,[1] in describing specimens of gold from the Breckenridge district in

[1] F. L. Ransome, *U. S. Geol. Survey, Professional Paper No. 75*, pp. 81–82.

Colorado says, "The leaf gold is in exceedingly irregular masses, many of which consist of thin septa meeting at angles that strongly suggest deposition controlled in part by the cleavage planes of a rhombohedral carbonate of the calcite group. . . . . The [wire] gold does not occur in the clean, bright condition familiar in cabinet

FIG. 2.—Gold replacing iron carbonate. × 2

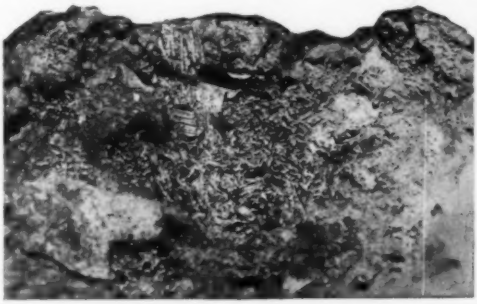

FIG. 3.—Gold replacing iron carbonate. × 2

specimens, but is imbedded in a reddish, earthy matrix, consisting largely of limonite, with oxides and carbonates of copper and various earthy impurities."

No doubt iron-bearing calcite can cause a similar precipitation, providing the iron is in the ferrous state of oxidation. Calcite is, of course, much more abundant than siderite in most gold

deposits. Analyses of calcite often show small amounts of ferrous carbonate, ranging in some cases up to 6 per cent. In sixteen analyses reported by Doelter[1] only three showed no ferrous iron, and the average for the sixteen was 1.33 per cent, reported as FeO.

Magnetite and olivine were selected as fairly simple ferrous compounds, and were allowed to stand in contact with a 0.5 per cent gold solution for 60 days. Neither one showed any precipitation of gold.

IV. MANGANOUS COMPOUNDS

a) *Manganous salts in solution.*—The fact that manganous salts, under certain conditions, can precipitate gold from solution and at the same time be oxidized to the insoluble manganese dioxide, seems to have escaped the attention of chemists. At least the writer has searched through chemical literature in vain for information on the subject. Wells[2] has called attention to the increased ease of oxidation of manganous salts in alkaline solutions, but the application to precipitation of gold has not been made.

The interesting occurrences of gold and manganese dioxide in a number of localities, notably in the San Juan,[3] Crede,[4] Park City[5] and Red Cliff[6] led to the suspicion that under the proper conditions manganous salts might act as the precipitating agent according to some such reaction as the following:

$$2AuCl_3+3MnSO_4+12H_2O=2Au+3MnO_2+6HCl+3H_2SO_4$$

Since this is the reverse of the reaction believed to be responsible for the solution of gold in the surface alteration of ore bodies, it is to be expected that it proceeds in this direction only under certain conditions, and the following series of experiments was undertaken with a view to ascertaining these conditions.

Gold chloride solutions of varying concentration were mixed with manganous sulphate solutions with concentrations ranging

[1] C. Doelter, *Handbuch der Mineral-Chemie*, I, 274–75. (Dresden, 1911.)

[2] Cited by W. H. Emmons, *Trans. Am. Inst. Min. Eng.*, XLII, 29 (1911).

[3] Ransome, *U.S. Geol. Survey, Bull. No. 182*, p. 101 (see also Emmons, *op. cit.*, 31).

[4] Emmons and Larsen, *U.S. Geol. Survey, Bull. No. 530.*

[5] *U.S. Geol. Survey, Professional Paper No. 77*, p. 103.

[6] S. F. Emmons, cited by W. H. Emmons, *op. cit.*

from normal up to saturation, but no precipitation occurred, even when the solutions were boiled for several minutes. All of these solutions gave acid reaction, due partly to the hydrolysis of the auric chloride:

$$AuCl_3+3H_2O=Au(OH)_3+3HCl$$

and partly to the addition product of auric chloride and water, H_2AuCl_3O, which ionizes as an acid[1] as follows:

$$H_2AuCl_3O=2H^++AuCl_3O^=$$

It is well known that the efficacy of many reducing agents is increased by the alkalinity as is readily explained by the electrolytic theory of oxidation and reduction.[2] In accordance with this theory it was thought that neutralization of the acid solution might induce precipitation. N/50 potassium hydroxide was slowly added to 10 c.c. of a solution N/5 with respect to manganous salt and containing 75 mg. of gold as chloride. When about 6 c.c. had been added a brown precipitate began to form. The alkali was added until the solution was nearly neutral with respect to litmus, the precipitate was collected on a filter, and the manganese oxide was removed by digesting with a mixture of oxalic and sulphuric acids of known reducing strength. The residue was brought into a crucible, dried, and shown to be metallic Au.

In order to determine which oxide of manganese was formed in this reaction, the solution in the oxalic and sulphuric acid was divided into two equal parts. One of these was analyzed for manganese, and the other titrated with standard potassium permanganate solution to ascertain the loss of oxalic acid due to oxidation by the manganese oxide. The titration showed an oxidation of oxalic acid corresponding to one atom of oxygen for every molecule of MnO as determined in the analysis for manganese. The precipitate was clearly MnO_2, doubtless with water of hydration. In a check experiment the manganese oxide was taken into solution with a mixture of oxalic and sulphuric acids, equivalent to 45.28 c.c. N/10 alkali. After dissolving the precipitate the solution was equivalent to 32.26 c.c. N/10 alkali, having lost the equivalent

[1] Hittorf and Salkowsky, *Zeitschr. f. Phys. Ch.*, XXVIII, 546–55 (1899).

[2] See Stieglitz, *Qualitative Analysis*, Part I, 269 ff.

of 11.02 N/10 acid. The manganese in solution was then converted to manganese dioxide by a standard method[1] and redissolved in the standard mixture of oxalic and sulphuric acids. Essentially the same loss of acid was obtained (10.89 c.c.), proving the first precipitate to be manganese dioxide.

The equation for the precipitation may be written as follows:

$$2AuCl_3+3MnCl_2+12KOH=2Au+3MnO_2+6H_2O+12KCl,$$

or, ionically:

$$2Au^{+++}+3Mn^{++}=2Au^{+}+3Mn^{++++}$$

It is evident from the preceding experiments that the precipitation may start before all the acid is neutralized, depending on the concentration of gold and manganous salt in the solution. Consequently substances which can partially neutralize the acid ought to induce precipitation. To test this conclusion a mixture of gold and manganous chlorides[2] in solution was made up as before, and small crystals of calcite were added. After 3 days the crystals were entirely coated with a brown precipitate of manganese dioxide (hydrated) and particles of gold were distinctly visible on close inspection. The equation may be written:

$$2AuCl_3+3MnCl_2+6CaCO_3=2Au+3MnO_2+6CaCl_2+CO_2$$

b) *Manganese carbonate.*—In the similar way it was shown that rhodochrosite can cause the precipitation of gold. In this case the reaction doubtless involved an additional stage, as follows:

$$MnCO_3+2HCl=MnCl_2+CO_2+H_2O,$$

after which the reaction was analogous to the one obtained with calcite, with the substitution of $MnCO_3$ for $CaCO_3$. In both cases carbon dioxide was evolved in noticeable quantity. Doubtless manganiferous calcite can react similarly.

It must be admitted that the concentration of gold and manganous salts used in these experiments were greatly in excess of any reported mine waters, but higher concentrations were necessary in outlining the nature of the chemical reactions involved. It remains to be shown that similar reactions can take place in extremely dilute solutions. Accordingly a liter of N/500 manga-

[1] Clowes and Coleman, *Quantitative Analysis*, p. 259.

[2] $MnCl_2$ was used instead of $MnSO_4$ to avoid the precipitation of gypsum.

nous chloride solution was made up and 38 mg. of gold in the form of chloride was added. Very dilute potassium hydroxide solution was added in small amounts, with repeated shaking until the solution was almost neutral to litmus. Precipitation occurred at once. The precipitate was allowed to settle for 24 hours, then all but 100 c.c. was decanted by means of a slow siphon. The remaining solution was filtered and added to the decanted portion. A 50 c.c. portion was tested for gold by the phenyl hydrazine test[1] in a Nessler tube, with blank for comparison. As this showed no gold, 500 c.c. of the solution was concentrated to 100 c.c. and the test was repeated. This again gave negative results. The test used readily detects concentrations of less than one part per million, consequently the second test showed the gold remaining in the original solution to be less than two parts in ten million. Since the precipitation is so complete we are forced to the conclusion that these reactions can take place in solutions of extreme dilution—such solutions as would be formed in the leaching of gold from a manganiferous lode.

The fact that in certain cases mine waters actually show alkaline reaction is well established. Emmons[2] has shown that at Ducktown, Tenn., the waters show decreasing acidity with depth. This was for water in an abandoned shaft. For circulating waters the change is probably greater. It is doubtless due to interaction with the constituent minerals of the surrounding rocks.

The following list gives the more common gangue and rock-forming minerals showing alkaline reaction to litmus or phenolphthalein:[3]

[1] The phenyl hydrazine test mentioned has been described by Pozzi Escot, *Ann. de Ch. Anal.* (1907), XII, 90–91. It consists in adding to the solution to be tested, a few drops of formic acid, then a few drops of saturated phenyl hydrazine hydrochloride. The presence of gold is shown by a purple tint which may be used in the colormetric estimation of small amounts of gold. This method as tested by the writer gave strong tint in a 50 c.c. Nessler tube to solutions containing nine parts of gold in ten million of water. The advantage over the oxalic acid test is that the reaction is almost instantaneous and no heating is necessary.

[2] W. H. Emmons, *U.S. Geol. Survey Bull. No. 470*, p. 172.

[3] Kenngott, *Neues Jahrbuch* (1867), p. 302; F. Cornu, *Tschermak Mitteilung*, XXIV, 417–32, *a* XXV, 489.

Feldspars	Olivine	Calcite	Vesuvianite
Micas	Serpentine	Aragonite	Noselite
Pyroxenes	Talc	Dolomite	Sodalite
Nephelite	Tourmaline	Magnesite	Hauynite
Spodumene	Apatite	Siderite	

It seems certain that if gold in solution escapes precipitation by sulphides, ferrous compounds, etc., and if gold and manganese-bearing solutions remain in contact with ordinary wall rock or gangue minerals for sufficient length of time, the acidity will be sufficiently reduced to allow the simultaneous precipitation of gold and manganese dioxide in the ore body.

It must be noted in this connection that the amount of manganese dioxide mixed with the gold is usually far in excess of that required by the equation given on p. 262.

Ferric salts, the most abundant oxidizing agents in mine waters, do not oxidize manganous salts to manganese dioxide, even in alkaline solutions. This was shown experimentally by making a solution of manganous sulphate and ferric sulphate, and slowly neutralizing the solution. Iron hydroxide was precipitated at once, but the manganese remained in solution until the solution became alkaline, when it was precipitated as manganous hydroxide.

Wells[1] has suggested an explanation for the precipitation of manganese oxides below the zone of acid waters, by the presence of small amounts of permanganates in the mine waters, which react with manganous salts to form manganese dioxide as follows:

$$2KMnO_4 + 3MnSO_4 + 2H_2O = 5MnO_2 + K_2SO_4 + 2H_2SO_4$$

The acid liberated is taken up by alkalies in case of an alkaline solution. This reaction has been used in the volumetric determination of manganese and is doubtless important if permanganates are present. No data available show permanganates in mine waters, and this theory needs verification before it is accepted as correct. However, it seems to be the nearest approach to an explanation of the precipitation of the excess of manganese dioxide over the stoichiometric proportion to gold, or the precipitation of the substance in any conspicuous amounts. The order of pre-

[1] R. C. Wells, cited by Emmons, *Trans. Am. Inst. Min. Eng.*, XLII, 29 (1911).

cipitation would, in general, depend on the concentrations of permanganate, gold chloride, and manganous salt, and the acidity of the solution; a complex relationship which has not as yet been worked out.

V. OTHER INORGANIC SUBSTANCES

The number of inorganic substances capable of chemically precipitating gold, and occurring in ore deposits or mine waters, is doubtless rather large, but the more important ones only have been discussed.

Sulphur dioxide is used as a precipitant for gold, and either crystalline or colloidal gold may be formed by the action of this substance or sulphurous acid on solutions of gold chloride, the state of the gold depending upon conditions of temperature, concentration, etc.[1] Sulphur dioxide however is comparatively rare in mine waters, and probably may be neglected so far as precipitation of gold in an ore body is concerned. Similarly arsenious acid, and doubtless a great number of substance may be disregarded.

VI. ORGANIC COMPOUNDS

That a very great number of organic compounds can precipitate gold is very well known, and the idea that such precipitations occur in nature is by no means new. Rickard's experiments with the Rico shale[2] have been frequently referred to in the literature of ore deposits. Practically all organic compounds found in nature are reducing agents, and a very great number are strong enough to precipitate gold. Formic acid, oxalic acid, acetylene, glucose, and a host of others belong to the list.

Just what compounds are present in a carbonaceous shale, and just which of those present cause the precipitation, is at present impossible to say, but that many of them can cause precipitation seems unquestionable.

Amorphous carbon is capable of taking gold from gold chloride solution by absorption.[3] This seems to be a physical action

[1] See Gmelin-Kraut, *op. cit.*

[2] T. A. Rickard, *Trans. Am. Inst. Min. Eng.*, XXVI, 978 (1896).

[3] S. Brussow, *Zeitschr. Kolloid Chem. Ind.*, V, 137–38 (1909).

rather than a chemical, but amorphous carbon may be present in carbonaceous shales and supposably might cause such precipitation. Whether other amorphous substances are capable of causing such precipitation has not been rigorously investigated.

SUMMARY

If gold is in solution in waters circulating through an ore body many substances may cause precipitation of the gold. The ferrous compounds, derived from the partial oxidation of iron sulphides, are thought to be the most important, because they are formed comparatively readily from pyrite and other iron-bearing sulphides by the action of oxidizing waters,[1] they are very often, if not usually present in mine waters, and they are very effective precipitants for gold. The effect of the iron-bearing sulphides themselves cannot readily be separated from the action of ferrous salts, since in precipitating gold they may lead to the formation of ferrous sulphate, which, of course may cause farther precipitation of gold, if any is present. In most gold deposits sufficient pyrite, or other iron-bearing sulphide is present in the primary ore, to precipitate any gold that may be brought to the zone of sulphides. Less commonly siderite or iron-bearing calcite may be important. Siderite is attacked by acids more readily than pyrite, and consequently gives up ferrous salts more easily, and these, in solution, may cause the precipitation.

In comparatively rare cases, when the gold is in a solution containing manganous salts, contact with the country rock may neutralize the acids present and allow the manganous salt to reduce to gold. Rhodochrosite resembles siderite in its action except for the fact that no precipitation of gold can occur if the solutions are strongly acid, while in the case of siderite acidity does not inhibit the reduction of gold chloride to metallic gold.

The other reducing agents considered are thought to be of comparatively little importance, as they may be applied, to only a very few unusual deposits.

No attempt is made to explain the precipitation of gold from

[1] Buehler and Gottschalk, *Econ. Geol.*, V, 28–35 (1910), and VII, 15–34 (1912).

alkaline sulphide solutions, suggested by Lenher[1] as a possible means for the transportation of gold, as such solutions are not formed in the alteration of gold deposits. Their adequacy as a means for transportation and primary deposition of gold is beyond the scope of this paper.

In conclusion the writer wishes to express his thanks to Professor W. H. Emmons, who suggested this investigation, and to Professor Stieglitz, of the Department of Chemistry, for many helpful suggestions, on both theoretical considerations and practical experimental methods.

[1] Lenher, *Econ. Geol.*, VIII, 744–50 (1912).

ORIGINAL STREAMS; AND THEIR RÔLE IN GENERAL DESERT-LEVELING

CHARLES R. KEYES

Of all continental features rivers seem longest to persist through the geologic ages. The ocean's strand-line freely oscillates as relatively the land-surface rises or sinks, but watercourses flowing to the sea are little disturbed. They may be turned aside; but they usually quickly adjust themselves to the new conditions by merely lengthening or shortening their lower reaches. Some streams, we know, hold their original courses in spite of all orogenic obstacles thrown across their paths. Others conform closely to the local warpings of the earth's crust. Still others greatly extend their valleys by headward growth. But whether antecedent, consequent, or subsequent rivers, they are all directly descended from prior drainage-systems which stretch out indefinitely through geologic time and which even trace back their ancestry to the very beginnings of continents. Nowhere and at no time is there spontaneous generation of new streams or total extinguishment of old ones. Indeed, in a normally humid climate it could hardly be otherwise. In this respect, recorded observation and the necessary consequences of theory strictly accord.

In arid regions there appear to be certain phases of drainage which have no counterpart in moist lands. What little running water there is, is confined mainly to the slopes of the loftier desert ranges. In the mountainous deserts of southwestern United States, for instance, the rivers which once traversed the region and which once were supposed to have carved out the present great valleys are regarded as having long since lost all traces of their courses. With increasing aridity came general withering of streams. Hence only remnantal drainage now seemingly remains. The headwaters of the small intermittent streams are regarded as representing all that is left of former great rivers which have vanished under

the influences of a desiccating climate and as vast volumes of mountain waste deeply filled their valleys to form the present level intermont plains. As these arroyos are looked upon today they are the last vestiges of a once extensive consequent drainage.

In this connection one other point should be briefly noted. The general plains-surface of the region under consideration lies about a mile above sea-level; and above this surface rise another mile the rugged and isolated desert ranges. As in the case of the Great Basin region, it was long the custom to regard the mountain-ranges as tilted and upraised blocks, deeply dissected on all sides from which the resulting waste was carried directly out into the intermont basins. According to this view, the arid climate came over the region while it was already a mountainous country, much as it is today except more deeply sculptured, like the Rockies or the Appalachians are now.

There is another hypothesis applicable to the origin of these streams of the desert ranges; one which more closely accords with the conditions imposed by an arid climate. It is postulated that the mountains are products of differential erosion on an elevated plain composed of alternating hard and soft rock-belts.[1] The erosion of more than 5,000 feet is ascribed to deflation with little or no aid from stream-action.[2] That wind-scour under favorable conditions is amply competent to accomplish such work, that it is as potent an erosive agent as stream-corrasion and the washings of the rain in a moist climate is fully shown by the recent writings of many observers in various parts of the world, although in this country this subject has not as yet received the attention that it merits. Of these, mention may be made of the work of Obruchew[3] in central Siberia, of Walther[4] in North Africa, of La Touche[5] in the western Rajputana in India, of Berg[6] and Ivchenko[7] in the

[1] *Journal of Geology*, XVII (1909), 31.

[2] *Bull. Geol. Soc. America*, XXI (1910), 592.

[3] *Verh. Imp. min. Gesellsch. St. Petersburg*, (2), XXXIII (1895), 260.

[4] *Das Gesetz d. Wüstenbildung im Gegenwart u. Vorzeit*, 1900.

[5] *Mem. Geol. Sur. India*, XXXV (1902), 10.

[6] *Pédologie pour 1902*, p. 37.

[7] *Ann. géol. min. Russie*, VII (1904), Pt. I, 43.

region about the Sea of Aral and in the Kirghiz steppes, of Passarge[1] and of Davis[2] in the South African veld, of Penck[3] in Palestine, of Hundhausen[4] in southern France, of Barron[5] in eastern Egypt, and of Blackwelder[6] in Wyoming.

The development of the drainage-lines in desert regions under conditions of general deflation is an aspect of arid erosion which has not, so far as I know, received the critical notice that it seems to deserve. Want of special attention to this single point has done more than any other one factor to mislead all who have traveled through the mountainous arid tracts of America, regarding the true ineffectiveness of the stream-erosion. Particularly deluding have been the impressions gained in such lands as those of western America. In many mountainous belts of that region there is, indeed, an apparent approach to normal stream-action as it is known in humid climates. Upon this really quite restricted and peculiarly modified effect of normal stream-work has been based the usual scheme of the arid cycle.

As is well known, the stratigraphy of the northern Mexican tableland, for example, is peculiar and remarkable in that the resistant rocks are mainly segregated in the lower part of the geologic column and the weak rocks in great thickness are confined to the upper part. In pre-Tertiary times chiefly the country was profoundly faulted, the average displacements being between 3,000 and 5,000 feet. As recently shown,[7] this region suffered planation and uplifting before the imposition of arid climate. If at the beginning of the cycle of aridity the surface were a plain, the present lofty ranges must have been differentially developed through the more rapid deflation of the broad belts of weak rock now constituting the areas of intermont plain.

As the mountains rear their forms more and more above the general plains-surface while the latter is being gradually lowered

[1] *Zeitsch. d. deutsch. geol. Gesellsch.*, LVI (1904), Protokol, 193.
[2] *Bull. Geol. Soc. America*, XVII (1906), 435.
[3] *American Jour. Sci.*, (4), XIX (1905), 167.
[4] *Globus*, CX (1906), 46.
[5] *Topog. of Sinai, West. Port.*, p. 17, 1907.
[6] *Journal of Geology*, XVII (1909), 429.
[7] *Proc. Iowa Acad. Sci.*, XIII (1908), 221.

through deflation, they finally become local rain-provokers of some small influence. During the period of arid youth the streams developed on the mountain slopes become slowly larger and larger, and longer and longer, until as the region is about to pass into its maturity, they attain their maximum size and efficiency. The mountains are now at their loftiest, their sides are steepest, the intermont plain encroaches deepest into them, the moisture gathered about them is greater in amount than at any time before or than will be afterward, the mountain watercourses reach their greatest extension, notwithstanding the facts that they carry relatively little water, are intermittent in character, and their lower reaches seldom pass beyond the foot of the ranges. Instead of being headwater remnants of extensive stream-systems which have long since withered away under the arid climate, as is a necessary consequence of the adapted normal-cycle hypothesis, they must be regarded as original streams coming into being as the differential effects of regional deflation become more and more pronounced. With the advancement of physiographic maturity these streams must begin to wither, and as senile relief approaches, they must, with few possible exceptions, undergo complete obliteration.

It is the custom to regard all water-action upon the desert ranges as normal stream-erosion in the process of dissecting recently upraised orographic blocks. This hypothesis seems to fall at once when it is considered that the major faulting of the mountain-blocks, is as already stated,[1] mainly very ancient, and not modern as has been so long assumed. Certain effects of general deflation have greatly aided in imparting to the mountain sides the infantile aspects of the stream-work. As recently suggested[2] the locus of maximum lateral deflation in the desert ranges is at their base, where plain sharply meets mountain without the intervention of foot-hills. The hard mountain-rock is encroached upon at the level of the general plains-surface as the sea gnaws away a line of its bordering cliffs, until, in many instances, the surface of the intermont plain extends into the mountain-blocks distances of several miles.

[1] *Bull. Geol. Soc. America*, XXI (1910), 543.

[2] *Science*, N.S., XXIX (1909), 753.

If the deflative hypothesis of regional desert lowering and leveling be accepted, we have in the desert ranges a stream-type hitherto unrecognized. The streams of this class have had no history previous to the youthful stage of the present geographic cycle, they have no prospect of relations with streams of a later cycle. Their birth, their span of life, their extinguishment are definitely circumscribed. They are the only existing streams we know of that do not have some sort of inherited relations with the waters of previous geographic cycles. They are the only streams the complete life histories of which may be distinctly traced. They are the only streams whose origin is clearly fixed in time and sharply limited in space.

THE NATURE OF THE LATER DEFORMATIONS IN CERTAIN RANGES OF THE GREAT BASIN

CHARLES LAURENCE BAKER

The department of paleontology of the University of California has lately made three expeditions into different regions of the southwestern part of the Great Basin with the main purpose of collecting Tertiary mammalian fossils. Incidentally a considerable body of new facts relative to the deformational and physiographic history of the later Cenozoic have been gathered, and a brief summary of some of the more important of these is here presented. No greater degree of accuracy than that implied by a rapid reconnaissance can be claimed for these statements. They apply to the following sections: the southern Sierra Nevada from the vicinity of Mono Lake southward to a point beyond Tehachapi Pass; the Black Mountain Range; the Calico Mountains of the central Mohave Desert; the El Paso Mountains, a short low range running *en echelon* with the southern Sierra Nevada southwest of Walker Pass; the northern White Mountain or Inyo Range on the boundary line between Nevada and California; the northern Silver Peak Range; the northern Pilot Range; the southern Gabbs Valley Range; the Cedar Mountain Range west and northwest of Tonopah, in central western Nevada; and the intervening basins.

The main tentative conclusion reached is that the conception of the extensive development of *normal* or *gravity* block faults *of great displacement* originally advanced by Russell and LeConte, and subsequently adopted by King, is fundamentally erroneous so far as this portion of the Basin Range province is concerned. In the opinion of the writer the Basin Ranges are really mountains of tangential compression. The evidence for this view is both structural and physiographic. The block faults, first described by Gilbert, can apparently be explained in considerable proportion quite as well as "upthrusts"—in the sense in which this

term was first used by Powell and C. A. White—as by the old conception of normal or gravity faults. Such of the faults as are really of the tensional type are probably those formed by the stretching of competent brittle rock along the flanks or summits of anticlines. There is so much of very competent rock in that region, and this is so commonly deformed by fracture rather than by flexure, that faults are very greatly developed and are often of great displacement.

The key to the problem is an old erosion surface, locally approaching the condition of a peneplain. This bevels the folded strata, and these contain a fairly abundant mammalian fauna of later Tertiary age. These folded and beveled later Tertiary beds have now been found in three widely separated localities of the southwestern Great Basin, namely in central western Nevada, in the central Mohave Desert, and in a region on the border line between the Mohave Desert proper and the rest of the Great Basin. The erosion surface cut out of these beds is in places warped into synclines, which form the valleys between many Basin Ranges, and into anticlines, which form the isolated ranges. In other places it is faulted, forming grabens in the cases of Death and Owens valleys and possibly elsewhere, and in other and more numerous cases tilted blocks bounded on one side by a fault scarp. The longitudinal profile of a block-faulted range, as determined by Louderback and the writer, is essentially that of the longer axis of an anticline. From a point of maximum movement the amount of displacement gradually dies out in either direction into monoclinal flexures and finally into undisturbed strata. Some of the Basin Ranges, as first pointed out by Spurr and Ball, do not owe their present forms in any sense to faulting but are merely structural upwarps or a series of anticlines more or less modified by erosion. Many of the intermontane basins are plainly seen to be true synclinal spoon-shaped basins. Gilbert's original suggestion that many of the Basin Ranges have their greater portions buried under their own débris is true only in a limited degree, for the original bed rock is found exposed at various places from the centers to the peripheries of some basins. In many of the basins the alluvium has not buried the post-Miocene

erosion surface, the formation of which antedated the latest deformation. The processes of desert erosion and deposition in an arid climate may mantle the rock surfaces of the ranges almost to their summits, and yet give only a very thin veneer above the bed rock, as mining operations at Tonopah and elsewhere have shown. In the immediate proximity of great fault scarps, the piedmont alluvial fans are, however, usually of great thickness, as on both sides of Owens and Death valleys.

The second uplift followed the axes of the first later Tertiary deformation but it seems to have been less intense, for the non-competent later Tertiary sediments, which were intensely folded in places and even overthrust during the first deformation, have been only gently warped during the second. This fact can be determined by the shape of the deformations in the peneplain produced during the first cycle of erosion. How much of the original folding of the non-competent later Tertiary beds has been due to a movement laterally over the basement of competent rocks which may have deformed mainly by fracture, is not known.

Zones of faulting along the bases of ranges have been examined by the writer in the Calico Mountains of the Mohave Desert in the Silver Peak Range in western Nevada and on the south base of the Sierra Nevada east of Tehachapi Pass. The fault planes in these localities approach the vertical and some even overhang. There is in the Silver Peak Range a zone of faulting rather than a single plane of faulting. The upthrown side forming the scarp is made up of the more competent and more erosion-resistant rocks, while the less competent strata on the downthrown side are closely compressed and overthrust contiguous to the faulting. In the Death Valley region, where faulting has probably taken place on as great a scale as anywhere in the Great Basin, closely folded Tertiary strata, referred to the Miocene by Spurr and Ball, bound the valley side of the Funeral Range fault. It is difficult to conceive how this folding and thrusting can have been caused by tensional stresses manifested in normal faults.

Gilbert's original conception of block-faulted mountains is incontestable. Gilbert never held, to the knowledge of the writer,

that all of the ranges of the Great Basin were of the block-faulted type, nor, as far as the writer knows, did he ever express the opinion in writing that the block-faults were all the results of tensional stresses.

On the contrary, Gilbert expressly states, on pp. 61 and 62 of Vol. III, U.S. Geographical Surveys West of the 100th Meridian, the following:

> . . . . In the Appalachians corrugation has been produced commonly by folding, exceptionally by faulting; in the Basin Ranges, commonly by faulting, exceptionally by flexure. The regular alternation of curved synclinals and anticlinals is contrasted with rigid bodies of inclined strata, bounded by parallel faults. The former demand the assumption of great horizontal diminution of the space covered by the disturbed strata, and suggest lateral pressure as the immediate force concerned; the latter involve little horizontal diminution, and suggest the application of vertical pressure from below. . . . . It is, that in the case of the Appalachians the primary phenomena are superficial; and in that of the Basin Ranges they are deep-seated, the superficial being secondary; that such a force as has crowded together the strata of the Appalachians—whatever may have been its source—has acted in the Ranges on some portion of the earth's crust beneath the immediate surface; and the upper strata, by continually adapting themselves, under gravity, to the inequalities of the lower, have assumed the forms we see. Such a hypothesis, assigning to subterranean determination the position and direction of lines of uplift in the Range System, and leaving the character of the superficial phenomena to depend on the character and condition of the superficial materials, accords well with many of the observed facts, and especially with the persistence of ridges where structures are changed. It supposes that a ridge, created below, and slowly upheaving the superposed strata, would find them at one point coherent and flexible, and there produce an anticlinal; at another hard and rigid, and there uplift a fractured monoclinal; at a third, seamed and incoherent, and there produce a pseudo-anticlinal, like that of the Amargosa Range.

Spurr's general view that the present Basin Ranges owe their forms to folding modified by erosion, holds in part, but Spurr appears to have clearly recognized but one great deformation, the mid-Mesozoic, although he did mention the folding of Tertiary strata. He failed to recognize that the axes of later deformations often cut diagonally or at right angles across the axes of the mid-Mesozoic folding. The recognition of this fact was one of Louder-

back's main contributions; it was noted in several ranges by the geologists of the Fortieth Parallel Survey, and the writer has recently noted the same divergence of earlier and later axes of folding in two other Nevada ranges, the Pilot Range and the Cedar Mountain Range.

The recency of the movement to which the existing Basin Ranges owe their forms is such as to leave intact, in large measure, the superficial rocks of the lithosphere, even when these lie high in the zone that was affected by fracture during this deformation. We know this because there is still preserved much of the erosion surface developed previous to this deformation. It also happens that a large portion of this superficial rock is of a competent nature and, without any load, seems quite as likely, or more likely, to break than to fold. The Basin Ranges may very possibly have originated by tangential compression. Their present elevations and structures may be a joint product of the initial intensity of the deformative forces and of the relative resistance to deformation of the strata involved. This is a very elementary conception but is as far as the writer is willing to go on his present data.

The mid-Mesozoic deformation was apparently the most intense, the folds in the Death Valley region and in the Pilot Range being as close as those of the central Appalachians. The first later Tertiary deformation was probably on the whole less intense, although locally non-competent beds are closely crumpled and overthrust. The writer's studies have not been of such a detailed nature as clearly to separate the effects of these two movements on the older rocks. The most recent deformation is the least intense, at any rate as exhibited on the surface, but is the one which is responsible for the present orographic features of the Basin Ranges. What has happened in the zone of flow, or in the zone of combined fracture and flow, during this latest deformation, we have no means of knowing, since erosion has not yet laid bare these zones. But it is probable that in the southwestern portion of the Great Basin the competent brittle rocks at the surface or close to the surface have deformed somewhat differently from the dominantly sedimentary rocks of the Rocky Mountains, the Jura,

the California Coast Ranges, the central and northern Appalachians, the Alps, and the Himalayas, which are taken as classic types of tangentially compressed mountains.

There may be movements of mountain-making intensity in this province other than those outlined above; but these three have been found to be readily determinable. There are physiographic evidences of intermittency in the most recent uplift in central western Nevada.

EDITORIAL

CONTRIBUTIONS FROM ALLIED SCIENCES TO GEOLOGIC FUNDAMENTALS

Probably there never was a time in the history of our science when contributions from related lines of inquiry were more frequent or more vital than now. Certain it is that the related lines of inquiry were never before so numerous or so searching. Some of the results recently reached in geophysics, geodynamics, radioactivity, micro-seismology, geodesy, and other lines are singularly instructive. While it is scarcely possible for the working geologist, pressed to the limit by his own urgent inquiries, to keep a close watch on the procession of papers that pour forth from all the sciences that bear on his own, there is none the less need to follow as fast as may be in the wake of progress in related sciences.

Formal reviews and synoptical notices are indeed a great aid to this but as a rule these are prepared by those interested in the science to which the papers primarily relate, and for those so interested, and the bearings of these papers on geologic problems are rarely noted even if the author has dropped suggestions in this line. This need and this infelicity in the usual means of meeting it have given birth to the thought that it might be helpful if those geologists who have occasion to read in related sciences were to call the attention of their fellow-workers to points of special interest or value as they may find them, particularly if these points are such as seem likely to escape due appreciation. Of course if the new light comes with a dazzling flash, as did the Röntgen rays and the radioactive emanations it may be assumed that its own penetrating power will suffice, or if it comes in the disturbing fashion of seismic tremors these may be trusted to shake us up duly; but there are sources of light of a much gentler type that throw scarcely less luminosity on some of our dark problems. A note or a hint as these are met may serve busy fellow-workers a good turn. We venture at least to give the thought a trial.

If anyone feels that our science is losing something of its fearsome interest by the decadence of faith in the nether lake of fire, he may find some slight consolation by turning to the growing list of titles of this disturbing sort: "The Gravitational Instability of the Earth,"[1] "The Problem of Gravitational Instability,"[2] "On the Vibrations and Stability of a Gravitative Planet,"[3] and "On the Dilatational Stability of the Earth."[4] These themes open up quite a new line of inquiry relative to the central balancing of the earth. They imply the possibility that a symmetrical unstable centering of the earth's gravity is liable to pass into unsymmetrical stability. There is thus brought into consideration a possible diastrophism of a profound type. We take kindly to this for it seems a fresh line of support to the view that diastrophism may be as deep as the earth itself, a view that grows up naturally along with the thought of a growing earth with growing stresses at all stages. This view of gravitational instability may not be equally welcome to those who assign the earth a heart of gas, for if the central balance is ever unstable and becomes disturbed, the unbalanced stresses are favorable to the escape of the gas from its state of enormous compression and the stresses are withal well suited to aid in opening the way of escape.

If we feel forced to believe that the heart of the earth is less fluidal than we once thought, there is now the alternative of feeling quite sure that it is compressible. So long as we were taught that the atom was an ultimate thing, impenetrably hard and indivisibly coherent, there was ground to feel that when a planet became compressed in its central parts so that the atoms touched one another, compression could go no farther; but now that the approved picture of the atom is that of minute corpuscles revolving in orbits at prodigious velocities, some of them now and then flying the track and disclosing their small sizes and great speeds, the view of incompressibility loses all rational basis. Compressibility of

[1] A. E. H. Love, *Phil. Trans. Roy. Soc. London*, A, CCVII (1907), 171.

[2] A. E. H. Love, *Some Problems of Geodynamics*, University Press, Cambridge, England, 1911.

[3] J. H. Jeans, *Phil. Trans. Roy. Soc. London*, A, CCVII (1903), 157.

[4] Lord Rayleigh, *Proc. Roy. Soc. London*, A, LXXVII (1906).

the *atoms*, as well as reduction of interatomic space, is now definitely recognized as a possibility and even a probability by Richards[1] and others. The diastrophism of the atom is now to be a theme of inquiry, as well as the diastrophism of the earth.

Most of the old computations of geophysical application were based on assumed incompressibility, but mathematicians and geophysicists are already reworking their computations on the basis of compressibility. This finds expression in such recent titles as "General Theory of a Gravitative Compressible Planet," "Effect of Compressibility on Earth Tides," "Vibrations of a Gravitative Compressible Planet."[2]

It tallies well with the new ideas of compressibility that there should be coming to light new forms of familiar substances as these are forced to pass through changes of physical condition, particularly changes of pressure. Bridgman, in a group of notable papers,[3] recognizes *five solid forms of water*, and hints that there may be more. In this series of contributions there seems to us to be ground for the inference that molecular rearrangement may not improbably be a common rather than an exceptional property when conditions of pressure notably change. It is perhaps not too much to surmise that a *successon* of rearrangements of molecules may take place where there is a succession of marked changes of pressure, such, for instance, as would arise with increasing depth in the course of the earth's growth, assuming that it grew by solid accretions. Some few such rearrangements falling within the limits of the solid state are well known, but it now seems not unlikely that there may be a series of such rearrangements following the analogy of the five solid states of water treated by Bridgman.

[1] Theodore W. Richards, *Year Book No. 11*, Carnegie Inst. of Washington, 1912, p. 255.

[2] A. E. H. Love, *Some Problems of Geodynamics*, University Press, Cambridge, England, 1911.

[3] P. L. Bridgman, *Contributions from the Jefferson Physical Laboratory of Harvard University*, IX (1911), Nos. 4, 5, and 6; "The Measurement of Hydrostatic Pressures up to 20,000 Kilograms per Square Centimeter," *Proc. Am. Acad.*, XLVII, No. 11; "Mercury, Liquid and Solid, under Pressure," *Proc. Am. Acad.*, XLVII, No. 12; "The Collapse of Thick Cylinders under High Hydrostatic Pressure," *Phys. Review*, XXXIV, No. 1; "Water, in the Liquid and Five Solid Forms, under Pressure," *Proc. Am. Acad.*, XLVII, No. 13.

These contributions and the following one also strengthen the view that transitions of form take place by fractional action, portions passing to the fluid state and back again in succession while the larger portion at any one instant remains solid. It is of course well known that some geologists regard the deformations and movements of ice and of other crystalline rocks as a process of this kind, though more commonly assigned to viscous or plastic properties.

In the interest of sharper analytical discriminations, Johnson and Adams[1] have drawn clear lines of distinction between different *kinds* of pressure and their diverse effects. Their welcome paper clarifies a field over which fog has hung rather thickly. This clear demarkation of distinctions will no doubt help relieve "plasticity" of an overburden of service as the putative creature of hydrostatic pressure. It will then be free to come into proper service occasionally as *unbalanced* stress invokes it. Let us hope that the notion that *free and easy* movement goes with "pressure plasticity" may be honored with a place on the historic shelf, and that a place beside it may be reserved for its close cousin, the notion that "flow" of rocks under differential pressure carries the quality of facile fluency.

It is prudent to note, however, that new light is often only partial light, sometimes merely a dim dawning that may lead astray rather than make clear the true way. Some of the determinations of Tammann,[2] important as they are in themselves, were so interpreted at first as to seem to some geologists to lead back to the old view of fluidity wherever in the heart of the earth pressure is great, but the still more extended experiments of Bridgman with their acutely critical interpretations point to solidity and rigidity,[3] as do so many other lines of recent inquiry.

Most of these other lines are familiar, but the full significance of the determination of the body tide of the earth by Hecker[4]

[1] John Johnson and L. H. Adams, "On the Effect of High Pressures on the Physical and Chemical Behavior of Solids," *Am. Jour. Sci.*, XXXV, March, 1913.

[2] *Kristallisieren und Schmelzen*, Barth, Leipzig, 1903.

[3] *Op. cit.*, pp. 436, 437, 553–57.

[4] O. Hecker, "Beobachtungen an Horizontalpendelen," etc., *Veröff. d. Königl. preuss. geodät. Inst.*, 1907.

has not been adequately appreciated. Hecker found that the body tide rises directly under the tide-raising body. This implies that it is the tide of a rigid elastic body. Such a tide obviously has no effective influence in retarding the rotation of the earth by reason of lag; it is effective only in so far as energy is transferred by friction.

We have fallen much short of noting all the significant points in these valuable papers, but we venture to hope that the points cited may be helpful to some readers and may lead to an intimate acquaintance with the papers themselves. These seem to have a common trend, and to prophesy that we may in the near future tread a *terra firma* indeed, and may be permitted in time to build the history of the earth on a solid foundation in a literal as well as figurative sense.

T. C. C.

April 9, 1913

Reviews

Geological Expedition to Brazil and Chile, 1908–1909. By J. Woodworth. Bull. Mus. of Comparative Zoölogy, Harvard College, Vol. LVI. Shaler Memorial Series, No. 1. Pp. 137, figs. 37, pls. 37. Cambridge, Mass., 1912.

In commemoration of the long and distinguished services rendered to Harvard University by the late Dean Shaler, the alumni of that institution raised an endowment of more than thirty thousand dollars for the purpose of conducting appropriate investigations and publishing the results as a tribute to his memory. As the evidence of past glaciation was one of the lines of study which particularly commanded Professor Shaler's interest, and as he long ago anticipated the discovery of evidences of glaciers in the conglomeratic formations of the closing Paleozoic era, it seemed eminently fitting that a portion of the memorial fund be expended for further research on the Permian conglomerates of southern Brazil, the glacial origin of which was suggested by Dr. Orville A. Derby in 1888. This report is the result of an expedition organized for that purpose.

Following the itinerary and narrative of the expedition, there is given a brief outline of the geology of south Brazil based chiefly upon the publications of Derby and of Branner and the special report on the coal area by I. C. White. The formations which enter into the structure of southern Brazil may be grouped into the following terranes: (1) The belt of igneous and metamorphic rocks of the coast, including the Serra do Mar region, frequently classed as Pre-Cambrian and certainly Pre-Devonian. (2) The Devonian, including the sandstone cuesta of the Serra das Furnas and the overlying fossiliferous shales of Ponta Grossa in the state of Paraná. (3) The Permian series, including conglomerates and tillite beds as well as sandstones and shales, the latter coal-bearing in the south. (4) The Triassic sandstones and trap sheets, the latter making the escarpment known as the Serra Geral and its topographical equivalents elsewhere. (5) The Tertiary fresh-water deposits of the upland, and possibly along the coast. (6) The Recent deposits along the coastal borders, now slightly elevated.

The declared purpose of the expedition having been the investiga-

tion of the Permian glacial formations of southern Brazil, most attention was devoted to these interesting and significant deposits. Thick deposits of tillite were found quite extensively in the state of Paraná and in the adjacent portions of São Paulo and Santa Catharina. No glaciated rock floor, however, has yet been found in south Brazil, nor have the larger bowlders been found to bear striated surfaces, but the members of the expedition found ice-worn surfaces on pebbles and on fragments of rock ranging up to the size of a man's head. Distinctly striated pebbles had not been discovered previously in these deposits. While maintaining a position of reserve, Woodworth believes that the gorge of the Iguassu at the point where the railway crosses it at Serrinha Station affords evidence of two glacial epochs within the Permian.

The author refers to the hypothetical Gondwana-land and inquires whether it included Paraná-land. In particular he raises the question whether there was a land connection between South America and Africa in Permo-Carboniferous times. He follows Suess in thinking that the Atlantic Ocean basin may have had its origin in post-Triassic times! He says: "Certainly the assumption of an Atlantic trough in pre-Triassic times having anything like the present extent of the basin must be abandoned as being without sufficient geological evidence." He ends by saying: "We may conclude therefore that the geologist is free to converge the coasts of Africa and South America in Permian and earlier Carboniferous time as closely as any biological facts and geological evidences of land may demand for their explanation."

No doubt the great name Suess may warrant the taking of such convenient liberties with masses of continental dimensions, but to one who has toiled for a year or so on the ancient crustal wrinkles that face the South Atlantic it sounds like an excerpt from the Romance of Cataclysm.

As a possible aid to genetic hypotheses of low latitude glaciation the author cites at length from authorities to show the frequency and effectiveness of hailstorms in warm countries and elsewhere, and seems to lean toward an explanation of Permian glaciation along this line. He would perhaps have added to the value of his contribution if he had drawn a sharper line between hot-weather hailstorms that spring from violent columnar convection and which drop their ice product in the hot bed that gave them origin, on the one hand, and, on the other, the common case of frozen rain and sleet that form when the conditions are on the wavering line between freezing and not freezing. The former have the merit of giving an impressive demonstration of the nearness

of a glacial zone above us, while the latter are but details of the border ground of common ice precipitation.

The author confesses to uncertainty regarding the cause of the Permian and Pleistocene glaciations, but he takes only three sentences to do up "the recently elaborated hypothesis that glaciation may be brought about through the temporary reduction of the amount of carbon in the earth's atmosphere." He says this theory "leaves unexplained the shortly succeeding ice advances between whose dates no corresponding appreciable reduction in the carbon is registered by rock-making in the earth's crust." Something no doubt is to be allowed for infelicity in phrasing when one is giving so short a shrift to a theory, but the author seems to lack a close acquaintance with the view he rejects. There are different views in which carbon dioxide plays a part, but there is only one that has been "elaborated" in a geological sense. This view makes a radical distinction between a glacial period and its oscillations, as also between fundamental agencies that may bring on a glacial period and auxiliary agencies that can only impose oscillations on it. The glacial period in this view persists through the whole series of oscillations, and the fundamental agencies continue in effect and action throughout. The fundamental agency assigned by this hypothesis is world-wide diastrophism which acts on the atmosphere by the increased contact it gives, and leads to its depletion; it also acts physically and mechanically. The chief auxiliary agency assigned to the production of oscillations is the ocean which holds 90 per cent or more of all the free and semi-free carbon dioxide on the face of the globe. The ocean alternately absorbs and gives forth carbon dioxide as set forth in detail by the author of this view. It is misleading to say that this hypothesis "leaves unexplained" the glacial oscillations, for it not only offers an elaborate explanation but is without a rival in the explicitness with which it draws forth and lays emphasis on the character of these oscillations, particularly that singular combination of subequal ice advances with continually shortening time-intervals between them. The author was of course altogether at liberty to say that in his judgment the explanation is inadequate or incompetent, but readers will hardly commend his precision of statement when he tells them that it leaves unexplained the oscillations when in fact it offers the most explicit explanation yet put in print, except perhaps that of Croll on quite a different line.

In summarizing the geomorphology of south Brazil the author brings out clearly the two distinct topographic units, the tableland, or

planalto, and its steep coastal border which constitutes the Serra do Mar. The region was baseleveled in the late Mesozoic, and the summits of the Serra do Mar which rise above the plateau level were probably more resistant granitic bosses which had not been reduced to the base plain. Uplifts in Tertiary and subsequent times have contributed to the present elevation and to the existing status of erosion.

The bulletin closes with a note on the changes of level on the coast of southern Chile. Starting out with the intention of studying the nature of the Pleistocene and Recent uplifting of the Chilean coast, first described by Charles Darwin, Woodworth failed to find good evidence of any extensive rise of the coast in Quaternary times. A late Pliocene or early Pleistocene uplift of about sixty feet at Valdivia, a late Pleistocene uplift of forty-five feet at Concepción, and a recent rise of lesser magnitude were indicated by these studies.

R. T. C.

"Formation of Coal Beds." II. By JOHN J. STEVENSON. *Proc. Am. Phil. Soc.*, Vol. L, No. 202, 1911.

The author of this article has prepared a careful survey of the literature bearing on the origin of coal beds. He has presented much data regarding the origin and character of transported organic matter and discussed the significance of floods and torrents as eroding and transporting agencies. There are three major divisions of the subject:

1. Rainfall barely disturbs the cover of litter in a forest and the latter is practically uninjured by the heaviest rainfall. Rainfall does not remove soil covered by vegetation unless this mantle is ruptured. Torrents produce but slight effects upon the rocks or vegetation over which they flow unless they carry considerable débris; trees of small and large diameter resist mountain torrents that are even loaded with coarse débris. Where the torrents come from regions having a good mantle of vegetable matter they are practically free from inorganic load.

2. Descriptions of peat deposits are included under this head and data from widely scattered regions are brought together showing the geographic and stratigraphic position of the beds, the botanical constitution, the appearance, thickness, and degree of consolidation. Peat consists of more or less altered plant material whose organic texture is recognizable and of an inclosing substance evidently derived from complete decomposition of the plant tissues. This is all more or less mixed with sedimentary sand, clay, or calcareous matter. Peat always contains a large amount of water. The fact is pointed out that peat does accumulate in the tropics

where topographic conditions are combined with the right humidity. Many peat beds are crowded with successive generations of trees growing on and in the peat and producing thick deposits.

3. Examinations of existing and buried peat beds has shown that they consist in part of trees and other vegetation *in situ* and of some drift material which can be recognized by its conspicuous lack of tender parts. There seems to be no difficulty in recognizing buried forests as such, and attention is called to the fact that in many great forested swamps broken and overturned stems are well preserved, while the stumps which have remained exposed to atmospheric action have decayed. The bedding and conformable relations of the various members of the coal series eliminate the probability of landslides as a great factor in coal formation.

E. A. STEPHENSON

Bulletin of the Seismological Society of America. Vol. I, No. 4, and Vol. II, No. 1.

This is devoted largely to seismology but is of great interest to the geologist as well as the seismologist. No. 4 contains a good biographical sketch of Major C. E. Dutton, an article on "Earthquake Epicentres," one on "Displaced Objects in Earthquake Motion," and an excellent contribution on some Canadian post-glacial faults, also many notes on recent earthquakes.

No. 1 of Vol. II contains biographical notes on Professor George Davidson and Professor John Milne, seismologist. Mr. Reid's article on the choice of a seismograph is interesting and valuable. The greater part of this number is devoted to a discussion of destructive earthquakes in China.

E. A. S.

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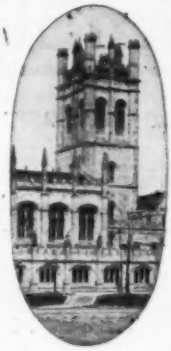

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